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WARFIGHTER PHYSIOLOGICAL STATUS MONITORING (WPSM): ENERGY BALANCE AND THERMAL STATUS DURING A 10-DAY COLD WEATHER U.S. MARINE CORPS INFANTRY OFFICER COURSE FIELD EXERCISE

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Energy balance and thermal status was assessed in 14 male U.S. Marine Corps volunteers (age = 25±3 y [mean±SD]; ht = 178±5 cm; wt = 81.0±4.1 kg; %body fat = 15±3; load = 42.6±3.2 kg) during a 10-day field exercise (FEX) at Quantico, VA. Question: Does intense physical activity, limited sleep, and restricted rations, combined with cold/damp weather, result in excessively negative energy balance and hypothermia? Methods: Total daily energy expenditure and water turnover were measured by doubly labeled water; daily food intake was assessed by ration wrapper collection; daily activity logs were maintained; weather data were collected with an automated weather station. Each volunteer wore wearable sensors that collected body core temperature, heart rate, activity patterns, and geolocation. Results: energy expenditure = 5378±678 kcal/d (22.51±2.84 MJ/d); energy intake = 1333±196 kcal/d (5.58±0.82 MJ/d); water turnover = 3.23±0.38 L/d. Carbohydrate intake was inadequate at 168±30 g/man/d. Rapid decreases in core temperature (~0.8 0C/h) were sometimes evident during inactivity/sleep. Conclusions: (1) one MRE ration per day provided inadequate carbohydrate - an additional 225 g/d of carbohydrate was needed to meet the minimum 400 g/d requirement, and (2) additional sleeping gear is needed to avoid rapid decreases in core temperature and sleep disruption.

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BACKGROUND

Commanders increasingly require basic information on the physiological status of their warfighters to meet operational and combat casualty care needs on the modern battlefield. The present study explored ways to meet this need by investigating the physiologic responses of Marine officers to the multi-stressor, cold-weather environment of an Infantry Officer Course field exercise. Ration wrapper collection was used to assess food intake; doubly labeled water method was used to assess total daily energy expenditure and daily water turnover. A prototype Warfighter Physiologic Status Monitoring (WPSM) system, consisting of miniaturized ambulatory physiologic sensors connected via a wireless network, was used to monitor core temperature (thermometer pill), wrist temperature, chest temperature, heart rate, geolocation (GPS) and activity/inactivity patterns (actigraphy). Meteorological data were collected by a local automated weather station. The data collected in this study should prove useful in developing and refining predictive algorithms, guiding incremental improvements in WPSM technologies, and refining training doctrine.

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EXECUTIVE SUMMARY

Metabolic energy balance and thermal status was assessed in 14 male U.S. Marine Corps (USMC) volunteers (age = 25±3 y [mean±SD]; ht = 178±5 cm; body wt = 81.0±4.1 kg; %body fat = 15±3; load wt = 42.6±3.2 kg) during a 10-day field exercise (FEX) at Quantico, VA. The FEX involved numerous attacks, forced marches, and night operations. Question: Does the intense physical activity, limited sleep, and restricted rations of the FEX, when combined with cold, damp weather, result in excessively negative energy balance and evidence of hypothermia? Methods: Total daily energy expenditure and water turnover were measured by the doubly labeled water method; food intake was assessed through daily collections of ration wrappers; daily activity logs were provided by each study volunteer; local weather data were collected with an automated weather station. Each volunteer wore a prototype Warfighter Physiologic Status Monitor (WPSM) system consisting of a network of wearable sensors that collected time series measurements of body core temperature (telemetry pill), heart rate (HR), activity (sleep/wake) patterns, and geolocation (GPS). Results: energy expenditure = 5378±678 kcal/d (22.51±2.84 MJ/d); energy intake = 1333±196 kcal/d (5.58± 0.82 MJ/d); water turnover = 3.23±0.38 L/d. Carbohydrate intake was inadequate at 168±30 g/man/d. Rapid decreases in core temperature (~0.8 ^{0}C/h) were sometimes evident during inactivity/sleep. Conclusions: (1) one MRE ration per day provided inadequate carbohydrate – these Marines needed an additional 225 g/d of carbohydrate to meet the minimum dietary carbohydrate requirement of 400 g/d, and (2) additional sleeping gear is needed to avoid rapid decreases in core temperature and the associated sleep disruption. For example, the bivy sack portion of the modular sleeping bag system (MSBS) could help avoid this "travel light, freeze at night" syndrome.

INTRODUCTION

U.S. MARINE CORPS INFANTRY OFFICER COURSE

The USMC Infantry Officer Course (IOC) is a 10 week Military Occupational Specialty (MOS)-producing school required of all Infantry Officers before assignment as platoon commanders within the operating forces. The bulk of the training takes place outside the classroom in simulated combat and tactical field exercises. The purpose of the course is to provide advanced infantry training for officers in preparation for duties as platoon commanders of rifle, weapons, anti-armor, heavy machine gun and mortar platoons. The course includes instruction on intelligence, advanced infantry tactics, fire support, assault combat engineering, infantry weapons, communications, aviation and close combat. Field exercises (FEX), field firing exercises and tactical decision-making scenarios are used to reinforce the classroom instruction. Performance-oriented instruction is aimed at teaching and applying maneuver warfare tactics directly related to company and battalion level Marine Air-Ground Task Force combat operations. Due to the favorable instructor-to-student ratio (1:5), students are provided individual guidance and training and are closely evaluated on an individual basis.

The culminating exercise for this course is an "IOC war" or field exercise (FEX) composed of a series of live and blank fire missions. The FEX is typically 9 to 10 days in duration and is designed to test the students' physical and mental endurance while applying the tactical lessons learned from earlier instruction. Training activities include a mechanized attack, an attack on a strongpoint, a tactical recovery of aircraft and personnel (TRAP), a non-combatant evacuation operation (NEO), and a raid. Conducting these training evolutions, as well as others, challenges the students with different scenarios covering the full spectrum of conflict. Students involved in the FEX operate on very limited sleep (~4 h/d) and one Meal-Ready-to-Eat (MRE) field ration per day (~1350 kcal or ~ 5.65 MJ/d), adding to the mental and physical stress. Each student receives an initial allotment of 5 MREs for the first 5 days of the FEX, followed by re-provisioning with an addition 5 MREs midway through the FEX. The "IOC war" is the final evaluation of what the students at the IOC have learned and how well they can apply it on a simulated battlefield with the stress of a battlefield environment. Volunteers for the present FEX study were drawn from the pool of IOC trainees.

STUDY RATIONALE AND OBJECTIVES

The Basic School requested USARIEM assess the energy balance and thermal state of trainees during a cold weather Infantry Officer Course FEX. The broad objective was to determine whether food restriction and cold weather placed undue strain on the trainees. Questions included (1) Does intense physical activity during the FEX, when combined with limited sleep and rations, and cold, damp weather, create conditions that are inherently unhealthy for the trainees? (2) Are caloric intakes sufficient to meet energy expenditure? (3) What activities are associated with the highest rates of energy expenditure? (4) Is there any evidence of hypothermia? (5) When is the risk of hypothermia greatest?

METHODS

Fourteen volunteers were recruited from an IOC class of about 58 U.S. Marine Officers. The study volunteers gave their free and informed consent after being briefed on the purpose, risks, and benefits of the study. This study was conducted in accordance with U.S. Army regulation AR 70-25, and U.S. Army Medical Research and Development Command regulation 70-25 regarding the use of human subjects in research.

At the start of the 10-day FEX, body weight and anthropometric measurements were recorded, and each volunteer was instrumented with a prototype Warfighter Physiological Status Monitoring (WPSM) system. The WPSM system, described below, measured heart rate, skin temperature at the wrist and chest, core temperature by ingested temperature pill, activity patterns by actigraph, and geolocation by global positioning system (GPS). In addition, daily ration wrapper collections were used to estimate food consumption in the field, and daily energy expenditure and water turnover was quantified by the doubly labeled water (DLW) method (see below). Local meteorologic data were collected by an automated weather station temporarily installed in the training area. Once a day the research team would rendezvous with the volunteers, who were all from a single squad. During these meetings, which lasted about 1 hour, urine tubes and individual ration wrapper collections were retrieved, WPSM data were downloaded and batteries replaced, and each volunteer filled out an hour-to-hour activity log for the previous 24 h period.

BODY WEIGHT, ANTHROPOMETRY, AND RESTING METABOLIC RATE

Semi-nude body weight was measured with a calibrated balance accurate to ±0.05 kg (Seca Model 770, Hamburg, Germany). This balance was also used for daily measurements of total weight which included all clothing, equipment, weapons, and water. Body fat was estimated pre- and post-study from abdomen circumference using an equation developed with U.S. Marine subjects similar to those in the present study (74):

$$FFM = (40.99 + 1.0435 \times BM) - (0.6734 \times \text{abdomen}),$$

where FFM = fat-free mass in kg, BM = body mass in kg, and abdomen = waist circumference in cm measured at the level of the navel. Three sequential measurements of abdomen circumference were made on each test volunteer by the same investigator using a spring-loaded fiberglass anthropometric tape. Fat mass was calculated as body mass minus fat-free mass. Resting metabolic rate (RMR) was calculated using the Cunningham equation (10):

$$\text{RMR, kcal/d} = 501 + 21.6 \bullet \text{body wt} - [\text{body wt} \times \text{\% body fat}],$$

$$\text{and RMR in kJ/d} = \text{RMR in kcal/d} \times 4.186$$

TOTAL DAILY ENERGY EXPENDITURE BY DOUBLY LABELED WATER

The doubly labeled water (DLW) method of estimating total daily energy expenditure (TDEE) is based on the assumption that after an initial oral dose of stable $^{2}H_2O$ plus $H_2{}^{18}O$, deuterium (^{2}H) is eliminated from the body as water, whereas ^{18}O leaves as both water ($H_2{}^{18}O$) and exhaled carbon dioxide ($C^{18}O_2$)(64). The rate of CO_2 production (VCO_2) can be calculated from the difference in elimination rates of the two isotopes. On the morning of day 0, the volunteers, who had refrained from eating or drinking for at least 12 h, reported to the testing area with a baseline sample of their first-void urine. After body weight was recorded and baseline saliva samples collected, 11 of the 14 subjects drank 0.30 g/kg body weight of $H_2{}^{18}O$ (Isotec Inc., Miamisburg, OH) and 0.09 g/kg body weight of $^{2}H_2O$ (MSD Isotopes, St. Louis, MO), as well as the 100 ml of tap water used to rinse the dose container. These tracers are stable, naturally-occurring isotopes. The remaining three volunteers, the placebo group, were treated in an identical fashion except that they were given tap water and their samples were used to monitor changes in background isotopic enrichment.

Saliva samples used to determine total body water (TBW) were collected in 4.5 ml tubes with silicone O-ring seals (Nunc, Roskilde, Denmark) 3 and 4 hours after the initial dose of DLW (65). The subjects were free to eat and drink only after the final saliva sample was collected. First morning void urine samples were collected on FEX days 1, 3, 5, 7, 9, and 10. All urine and saliva samples were stored in 4.5 ml tubes with silicone O-ring seals (Nunc, Roskilde, Denmark). Total daily energy expenditure was calculated using the linear regression method. Briefly, isotopic elimination rates for ^{2}H and ^{18}O were corrected for changes in baseline isotopic abundances (29). The rate of CO_2 production was calculated using the equations of Schoeller et al. (65). Energy expenditure was calculated from the rate of CO_2 production using metabolic fuel respiratory quotients calculated from food intake and body energy store combustion and conventional calorimetric relationships (45). Standard factors were used to correct for isotope fractionation in respiratory and cutaneous water efflux (65,66). Changes in isotopic baseline in the placebo group were used to correct the DLW TDEE calculations of the experimental group. Isotopic analyses were performed as previously described (11). Briefly, the ^{18}O abundances were measured by equilibration of fluid with CO_2. Measurements were done in duplicate with a SD of 3×10^{-5} atom percent (0.15‰). Deuterium abundances were measured by the zinc reduction method. Measurements were performed in triplicate with a SD of 1.7×10^{-5} atom percent (1.2‰). Isotope enrichments were calculated by taking the arithmetic difference between the per mil enrichment (9) of each sample and the respective pre-dose sample. The ratio of excess isotope was calculated and converted to atom percent excess (5).

WATER TURNOVER BY DEUTERATED WATER ELIMINATION

Total water flux, or water turnover, was calculated as the product of deuterium turnover, that is, the decline over time in isotopic enrichment of body water with $^{2}H_2O$, and the $^{2}H_2O$ dilution space (44,53). The isotopic enrichment of body water declines due to the elimination of labeled water via excretion and evaporation, and the influx of unlabeled water from dietary, metabolic, and atmospheric sources. The tritiated water elimination method has been

validated in animals (44), and the ^2H_2O elimination method of measuring preformed dietary water intake has been validated in humans (15). Typically, about 10% of the apparent total water influx can be attributed to metabolic water production and respiratory and cutaneous water influx, with the balance associated with preformed dietary water intake.

RATION CONSUMPTION

Each IOC student was initially provided 5 Meal Ready-to-Eat (MRE) field rations, with a second provisioning with five MREs on day 5, midway through the FEX. The food consumed during the FEX consisted almost exclusively of MRE rations (MRE versions 18 and 19). Food intakes were calculated from individual collections of the various wrappers from food consumed that day. Metabolizable energy intake was calculated by factoring quantities of individual food items consumed against their caloric content (Nutritionist 5; First DataBank, Inc, The Hearst Corporation, San Bruno, California). This process required manual entry of nutritional information for Meal-Ready-to-Eat (MRE) ration items into the Nutritionist 5 data base. Mean daily dietary intakes of protein, carbohydrate and fat during the field exercise were calculated for each subject. Overall group means and variance for macronutrient and energy intakes were calculated from these individual values.

ACTIVITY AND CLOTHING LOGS

Once a day, each volunteer filled in a sheet describing their hour-to-hour training activities for the previous 24 h. Since the volunteer group trained as a squad, these logs were consolidated into an overall activity record describing training activities. In addition, at the end of the study each volunteer provided a description of all the daytime and nighttime clothing items used during the FEX.

WEATHER DATA COLLECTION

A portable weather station (Model 10, Campbell Scientific, Logan, Utah) was installed in the fenced enclosure of the R-15 observation tower (grid reference 790710) on the Quantico Military Installation. This station automatically recorded ground and air temperature, black globe temperature, relative humidity, and wind speed at 5-minute intervals. Local precipitation records were obtained from the meteorologic station at the Marine Air Facility, Quantico.

PROTOTYPE WARFIGHTER PHYSIOLOGICAL STATUS MONITORING (WPSM) INSTRUMENTATION

The configuration of the prototype Warfighter Physiological Status Monitor (WPSM) system used in this study in shown in Figure 1. Each system weighed about 700 g (1.6 lbs) without GPS batteries, or 1032 g (2.3 lbs) with GPS batteries. The system consisted of a wireless radio frequency (RF) network of sensors to measure and record time series measurements of heart rate, chest and wrist skin temperatures, core temperature, activity patterns, metabolic cost of locomotion (boot strike monitor), and geolocation (global positioning

system, GPS). These sensors were attached to the wrist (activity monitor and wrist skin temperature), chest (heart rate monitor), boot (boot strike monitor), and Load Bearing Vest (LBV)(core temperature monitor, and GPS/hub). Geolocation was monitored with an off-the-shelf GPS system with an external antenna.

Sensor data was routed via a PAN to a central data processing point, or hub, where digitized data was stored. The sensors periodically and redundantly transmitted data to the hub receiver. Collisions between data packets occurred, but the slow data rate needed to monitor HR and Tcore changes allowed this simple approach to succeed. This PAN is typical of most other existing PAN technologies - that is, somewhat primitive and based on an ad hoc design that has a tendency to be brittle and error-prone. Alternate approaches using wired PANs risk snagging or connector failure and tend to restrict sensor and processor placement.

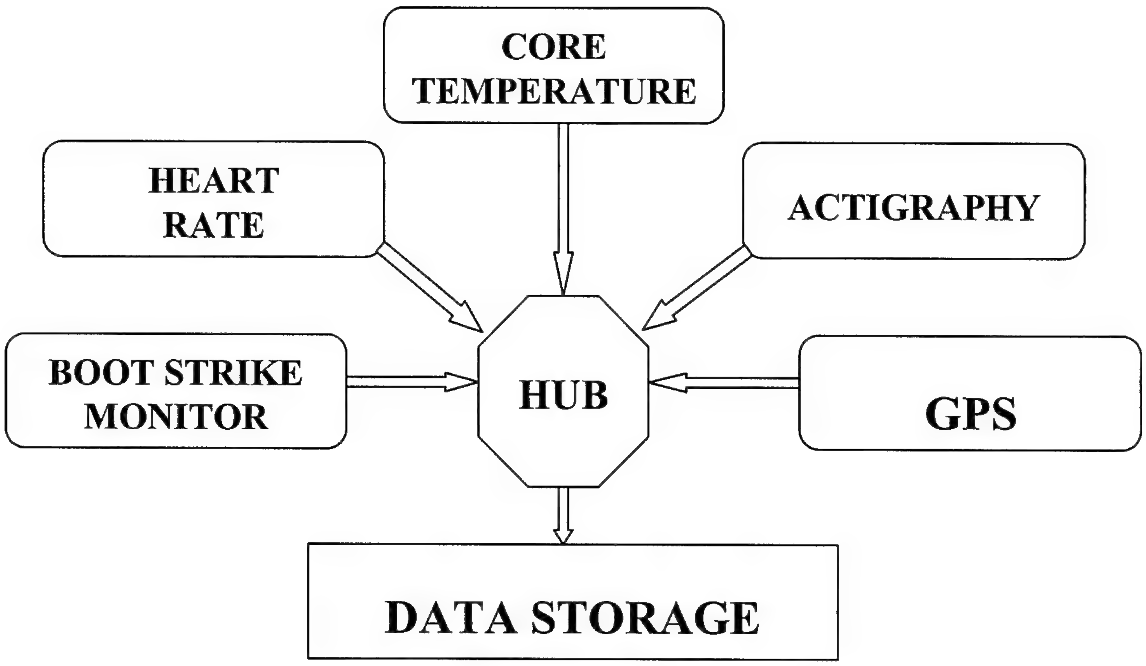


Figure 1. The boot strike monitor was mounted on the laces of the boot; the heart rate monitor sensor used a chest strap; core temperature was monitored by thermometer pill; activity patterns were monitored using a wrist actigraph, and global positioning system data were gathered with a GPS receiver mounted on the load bearing vest. The GPS and Hub were co-located in a single enclosure and were hardwired together. Otherwise, sensor data were transmitted wirelessly to the hub. Data streams were interleaved and stored by the hub.

Hub Interface

The hub interface device served as a router, receiving transmissions from each sensor on the network and storing time-stamped data for later retrieval and analysis. The hub shared an enclosure with the commercial-off-the-shelf global positioning system (Trimble Lassen SK8 GPS receiver, Trimble, Inc., Sunnyvale, CA). The GPS/Hub unit weighed 284 g, including hub batteries (166 g) and the GPS antenna, which mounted to top of the LBV shoulder strap. Batteries for the GPS weighed 332 g.

Heart rate monitor

The heart rate monitor, which weighed about 80 g, consisted of a commercial chest strap pickup (Vantage XL model; Polar Electro, Ft. Washington, NY) modified by Precision Control Design, Inc. (Fort Walton Beach, FL). These modifications included the addition of an over-the-shoulder strap to keep the chest strap in place, and the addition of an activity sensor (described below), a chest skin temperature sensor, and a radio transmitter.

Body core temperature monitoring

The core temperatures of the study volunteers were measured by a telemetry temperature pill system. Each test volunteer swallowed a standard 510K-certified ingested temperature telemetry pill (2.2 cm x 1.0 cm) (CorTemp^{tm}, Human Technologies Inc., St. Petersberg, FL). The ~260 kHz signal from the pill, which varied with temperature, was recorded by a Body Core Temperature Monitor (7.0 cm x 14.3 cm x 3.0 cm; 240 g)(BCTM 3; Personal Electronic Devices, Inc., Wellesley, MA).

The temperature pill method provides a valid measure of core temperature without the discomfort and inconvenience of a rectal or esophageal probe. Although no single definitive core temperature exists because of temperature differences among sites in the body (62), core temperatures measured at the esophagus, rectum, and gastrointestinal tract are considered the among the most scientifically legitimate representations. A close relationship among body core temperatures measured by esophageal probe, and rectal probe, and telemetry pill has been shown during exercise in temperate and hot conditions (19,39,67), as well as during cold conditions at rest and during exercise (54).

Activity monitor

An activity monitor worn on the non-dominant wrist was used to monitor activity patterns and wrist temperature (3.5 cm x 3.2 cm x 0.8 cm, 24 g)(Telemetric Sleep Watch, Precision Control Design, Inc., Fort Walton Beach, FL). The output of the monitor's piezoelectric motion sensor, recorded as "zero crossings" – that is, the number of times the output voltage crossed a zero volt threshold during a given 1 min epoch – was analyzed by an onboard microprocessor running the Cole-Kripke algorithm to differentiate activity from inactivity (6,29). These data, along with skin temperature, were transmitted once a minute to the hub as the number of minutes of inactivity in the preceding 15 min interval. In addition, a similar motion sensor mounted in the chest band transmitted activity as the number of zero crossing per minute.

Expended energy monitor (EEM)

An egg-shaped “expended energy monitor” (EEM) attached to the boot laces, was used to estimate the minute-to-minute metabolic cost of walking and running on level terrain from total weight (including load) and the time during each stride that a single foot contacts the ground (30,40,68)(EEM, Personal Electronic Devices, Inc., Wellesley, MA)(2.5 cm x 2.5 cm x 1.3 cm; 72 g). Total weight, measured each day, was used in the calculation of the metabolic cost of locomotion. The rate of metabolic energy expenditure during walking or running is primarily determined by the cost of supporting body weight and rate at which this force is generated (68). Thus, the rate of force generation can be estimated as total body weight divided by the time that a single foot contacts the ground during each stride (30,40). In addition, the empirical Pandolf equation was used to predict the metabolic cost of locomotion (M_{loco}) from movement velocity, external load, body weight, percent grade, and terrain characteristics (e.g., dirt road, snow, sand, etc.)(56). The development of the Pandolf equation is described elsewhere (59).

THERMAL STRAIN INDICES

During selected periods, a Cold Strain Index (CSI), and a Physiologic Strain Index (PSI) that provides an estimate of work/heat strain, were calculated for a subset of the seven male volunteers with complete data (age = 25±3 y [mean±SD]; ht = 178±5 cm; body wt = 81.0±8.9 kg; %body fat = 15±3; load wt = 42.6±3.2 kg).

Cold Strain Index (CSI) was calculated as:

$$CSI = 6.67(T_{core\,t} - T_{core0}) \cdot (35 - T_{core0})^{-1} + 3.33(T_{sk\,t} - T_{sk0}) \cdot (20 - T_{sk0})^{-1},$$

where T_{core0} and T_{sk0} are the initial measurements of core and mean weighted skin temperature, and $T_{core\,t}$ and $T_{sk\,t}$ are simultaneous measurements taken at any time *t*. In addition, if $T_{core\,t} > T_{core0}$, then $T_{core\,t} - T_{core0} = 0$ (ref. 50) and, in a modification of the original equation, if $T_{sk\,t} > T_{sk0}$, then $T_{sk\,t} - T_{sk0} = 0$ (personal communication, D.S. Moran). This latter modification was intended to correct for anomalously low CSI values during sleep when skin temperature typically rises and core temperature falls (72).

Physiological Strain Index (PSI) (49) was calculated as:

$$PSI = 5(T_{core\,t} - T_{core0}) \cdot (39.5 - T_{core0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1},$$

where T_{core0} and HR_0 are the initial core temperature and heart rate measurements, and $T_{core\,t}$ and HR_t are simultaneous measurements taken at any time *t* .

STATISTICS

Values are expressed as mean ± range or, where error bars are shown, as mean ± standard deviation.

RESULTS

STUDY VOLUNTEER CHARACTERISTICS

The age and physical characteristics of the 14 male Marine volunteers, the weight of the average load carried during the FEX, and resting metabolic rate (RMR) are shown in Table 1. Inadvertently, height was not measured in subject 9, and circumference measurements needed to estimate body fat and RMR were not done on subject 8, and final semi-nude body weights were not measured on subjects 2, 4, 5, 10, and 14. If mean body fat % for the group is used, RMR for subject 8 would be 1950 kcal/d (8.16 MJ/d).

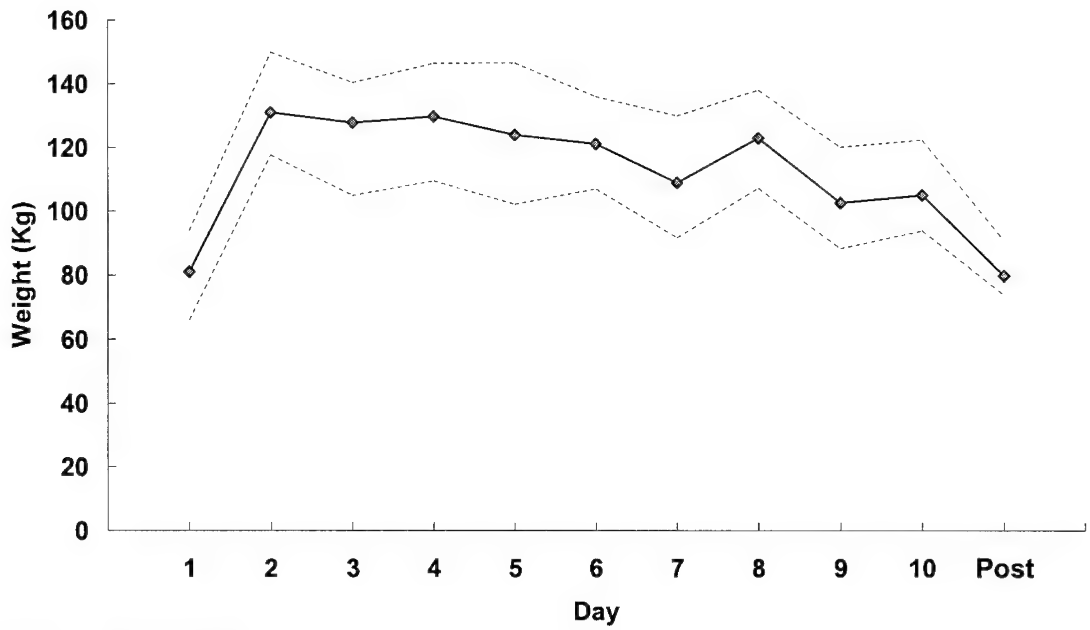
Daily total weights during the FEX are shown in Figure 2. The initial and final weights (day 1 and 10) are semi-nude weights, and the weights on days 7 and 9 are without packs. The various clothing items worn by the Marines during the FEX are listed in Appendix B.

Table 1. Study volunteer characteristics.

Subj. No.	Age (y)	Height (cm)	Nude Weight (kg)	Body Fat (%)	Load Carried (kg)	RMR* (kcal/d)
1	24	185	93.5	17.3	41.5	2171
2	25	170	66.1	16.5	41.0	1693
3	22	178	78.8	13.3	38.4	1977
4	29	175	70.3	8.8	42.9	1886
5	23	175	73.4	11.1	38.0	1910
6	30	185	93.9	18.4	44.2	2156
7	23	183	79.9	14.4	42.3	1978
8	30	177	79.2	---	42.7	---
9	22	---	82.9	18.0	45.8	1969
10	29	175	93.1	20.1	41.8	2108
11	24	185	80.8	15.8	42.9	1971
12	24	178	80.6	15.2	51.2	1977
13	23	170	72.5	15.6	40.7	1823
14	26	193	89.5	14.2	42.8	2160
Mean	**25**	**178**	**81.0**	**15.3**	**42.6**	**1983**
SD	**3**	**5**	**8.9**	**3.3**	**3.2**	**141**

*RMR = resting metabolic rate.
RMR, kcal/d = 501 + 21.6 (body wt - [body wt x % body fat])(ref. 10)
kJ/d = kcal/d × 4.186

Figure 2. Daily total weights during the FEX. The initial and final weights, on day 1 and post-FEX, are semi-nude weights, the weights on days 7 and 9 were total weight without packs.



TRAINING ACTIVITIES

The FEX started at about 0300 h on 3 March 1999 and ended about 2200 h on 12 March 1999. Activities associated with each training day are shown in the panel H of Figure 5.

WEATHER DATA

Daily meteorologic data, shown in the G panels of Figure 5, was collected by a weather station located north of an observation tower. A midday shadow cast by the tower is responsible for the transient midday depression in globe temperature. Measurable precipitation included rain on test Days 1, 2, 4, 5 (3, 4, 6, and 7 March 1999), and snow on Days 7 and 8 (9 and 10 March 1999).

ENERGY EXPENDITURE, FOOD ENERGY INTAKE, AND WATER TURNOVER

High TDEEs (Table 2) and restricted food energy and macronutrient intakes were associated with 3.3 kg decrease in body weight (Table 3).

Table 2. Total body water, oxygen-18 and deuterium elimination rates, total body water, total daily energy expenditure (TDEE), and energy expenditure expressed as a the ratio of TDEE to resting metabolic rate (RMR).

Subj.	TBW (L)	k_O day^{-1}	k_D day^{-1}	Water Turnover (L/d)	TDEE (kcal/d)	TDEE (kJ/kg/d)	TDEE/ RMR
1	Placebo	--	--	--	--	--	--
2	39.02	0.1039	0.0696	3.27	4246	268	2.5
3	Placebo	--	--	--	--	--	--
4	44.59	0.0873	0.0544	2.92	4729	280	2.5
5	48.85	0.0794	0.0436	2.56	5726	327	3.0
6	56.42	0.0863	0.0511	3.47	6446	289	3.0
7	Placebo	--	--	--	--	--	--
8	43.44	0.0987	0.0626	3.27	5032	268	
9	50.63	0.0853	0.0492	3.00	5943	301	3.0
10	Placebo	--	--	--	--	--	--
11	49.08	0.0888	0.0574	3.39	4918	255	2.5
12	48.72	0.0927	0.0563	3.30	5725	297	2.9
13	46.82	0.0901	0.0563	3.17	5075	293	2.8
14	55.16	0.0938	0.0602	3.99	5939	276	2.7
Mean	**48.24**	**0.0906**	**0.0561**	**3.23**	**5378**	**285**	**2.8**
SD	**5.22**	**0.007**	**0.0073**	**0.38**	**678**	**21**	**0.2**

Note: TDEE is in kcal/d and kJ per kg body weight per day.

The amount of food consumed each day varied widely (Figure 3), presumably due to variation in the time available to eat and the resupply schedule. Due to the consumption of unrecorded non-ration food items at the end of the FEX, food intake data are not reported for Day 10. Daily carbohydrate consumption, which averaged 168 g/d, is shown in Figure 4. A metabolic fuel quotient of 0.80, calculated from composition of the food consumed and body fat usage, was used to calculate DLW TDEE. The TDEE of the Marines was 2.8 ± 0.2 times the calculated resting metabolic rate. Body weight-specific TDEE was 49.6 ± 3.5 kcal/kg BW/d (208 ± 15 kJ/kg BW/d) with a range = 43.5 to 53.8 kcal/kg BW/d (182 to 225 kJ/kg BW/d). Total water flux, calculated as the product of deuterium turnover (kd) and total body water, averaged 3.23 ± 0.38 L/d.

Figure 3. Food energy intake by day. Rations were supplied at the start of the FEX and on day 5.

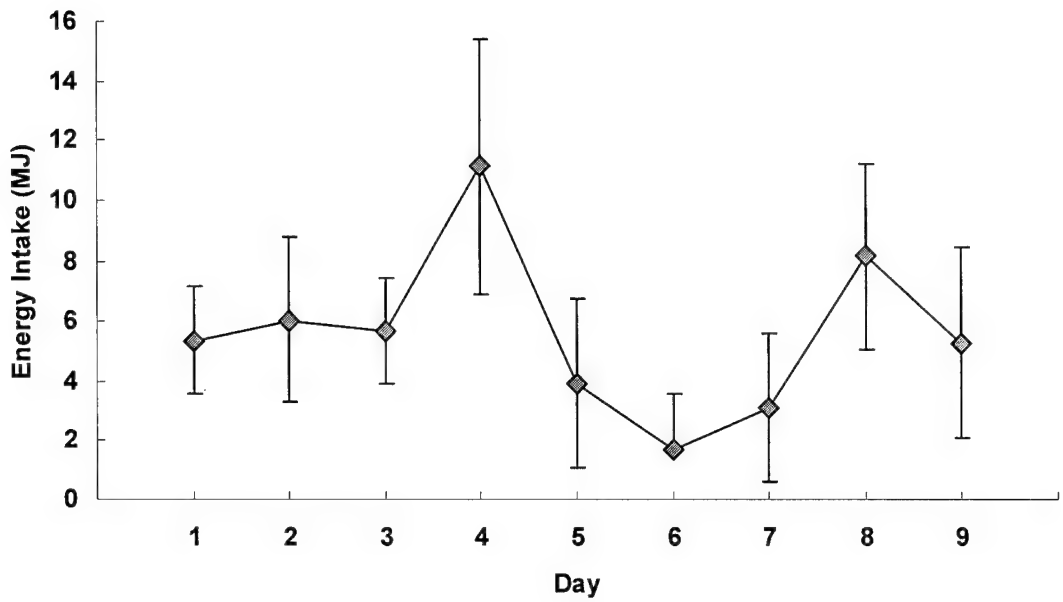
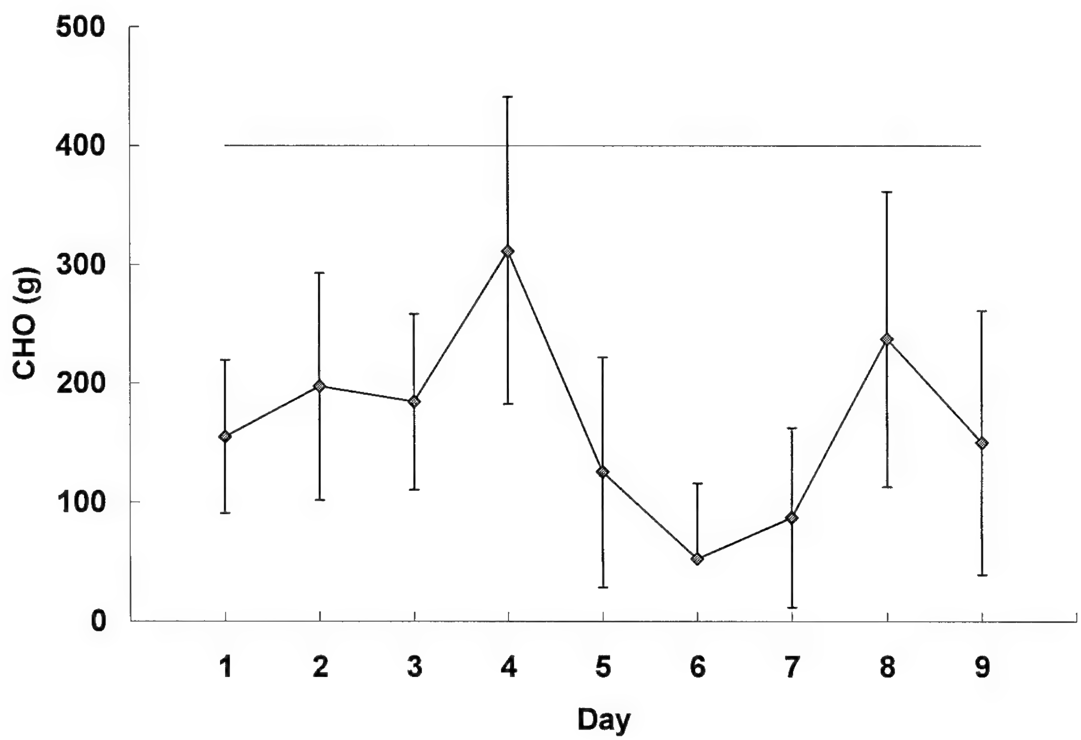


Figure 4. Daily carbohydrate intake, shown as means ± SD . Carbohydrates intake varied with ration intake and was below the 400 g/d intake recommended for physically active infantry in the field.



PHYSIOLOGICAL STATUS

Core temperature, wrist skin temperature, chest temperature, heart rate, chest actigraphy score, and mean sleep score, are shown in Figure 5, panels A-F. Due to sensor breakage, no useful data were collected from the expended energy monitors (EEM). In addition, data collection was interrupted whenever a volunteer removed his load bearing vest (LBV) since key monitoring and data logging components were attached to the LBV (hub/GPS unit and BCTM). Physically demanding FEX activities associated with heart rates above 140 beats per minute are shown in Table 4.

Cold and Work/heat Strain Indices

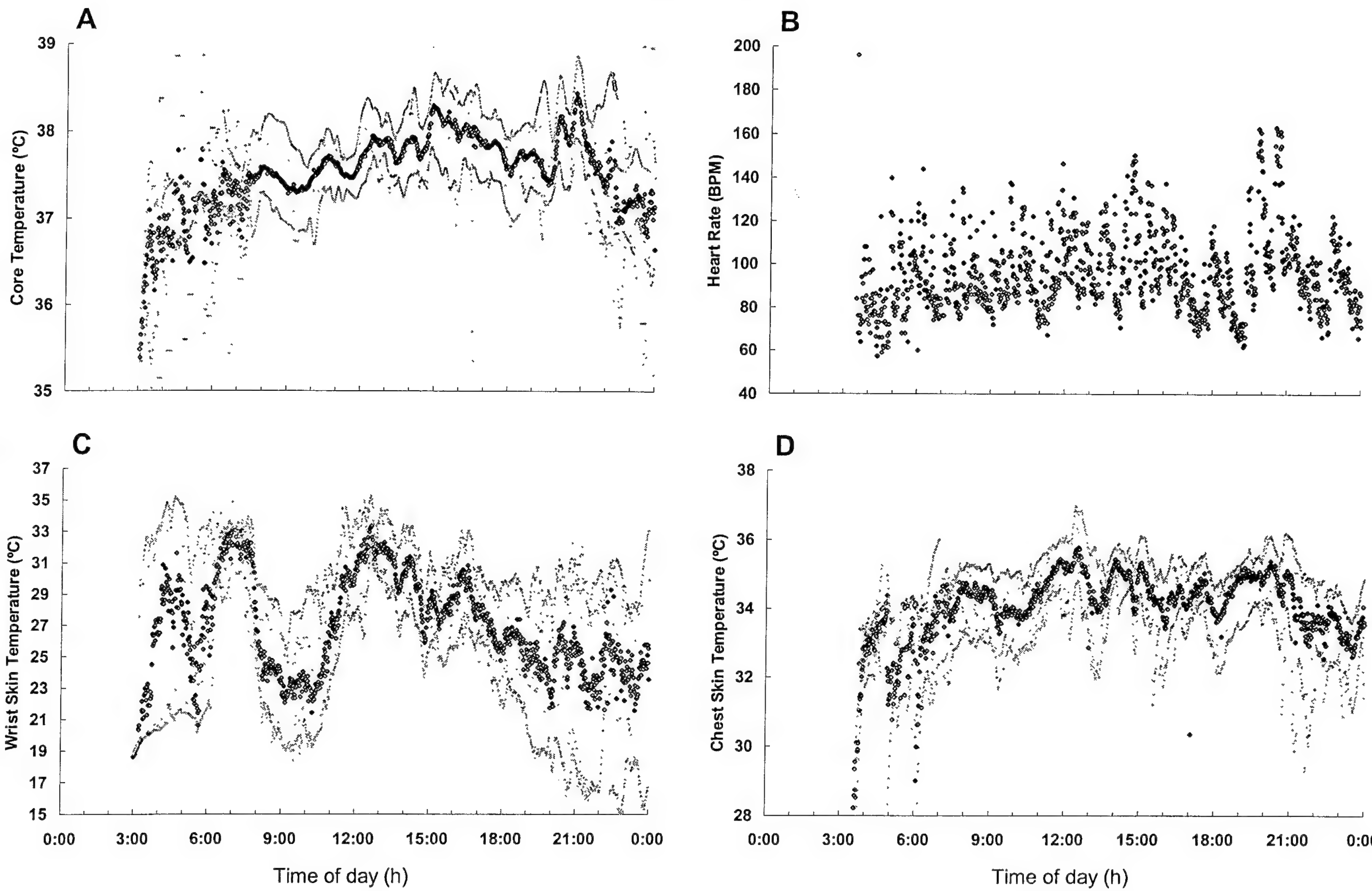
Average cold strain index (CSI) values were calculated for 90 min of moderate exercise (0037 to 0207 h) and 90 min of rest (0300 to 0430) on day 6. Mean Tc decreased from 37.3±0.13°C to 36.3±0.28°C (dTc/dt = -0.02°C/min), while skin temperature increased from 27.3±0.28°C to 32.1±0.62°C (dTskin/dt = 0.09°C/min). The CSI values index increased from near zero to 2.7±0.9 with the transition from marching to rest (Figure 6). Average physiological strain index (PSI) values (Figure 7) were calculated for day 5 (7 March 1999) for 70 min of moderate exercise (0918 to 1028 h) and 70 min of heavy exercise (1211 to 1321 h). The PSI values increased 8-fold (0.6±0.4 to 4.5±0.7), as HR (94±7 to 133±14 bpm) and Tc (36.9±0.1 °C to 37.9±0.2 °C)(dTc/dt = 0.01 °C/min) increased.

Table 3. Food energy intake, macronutrient intakes, and body weight loss during the field exercise.

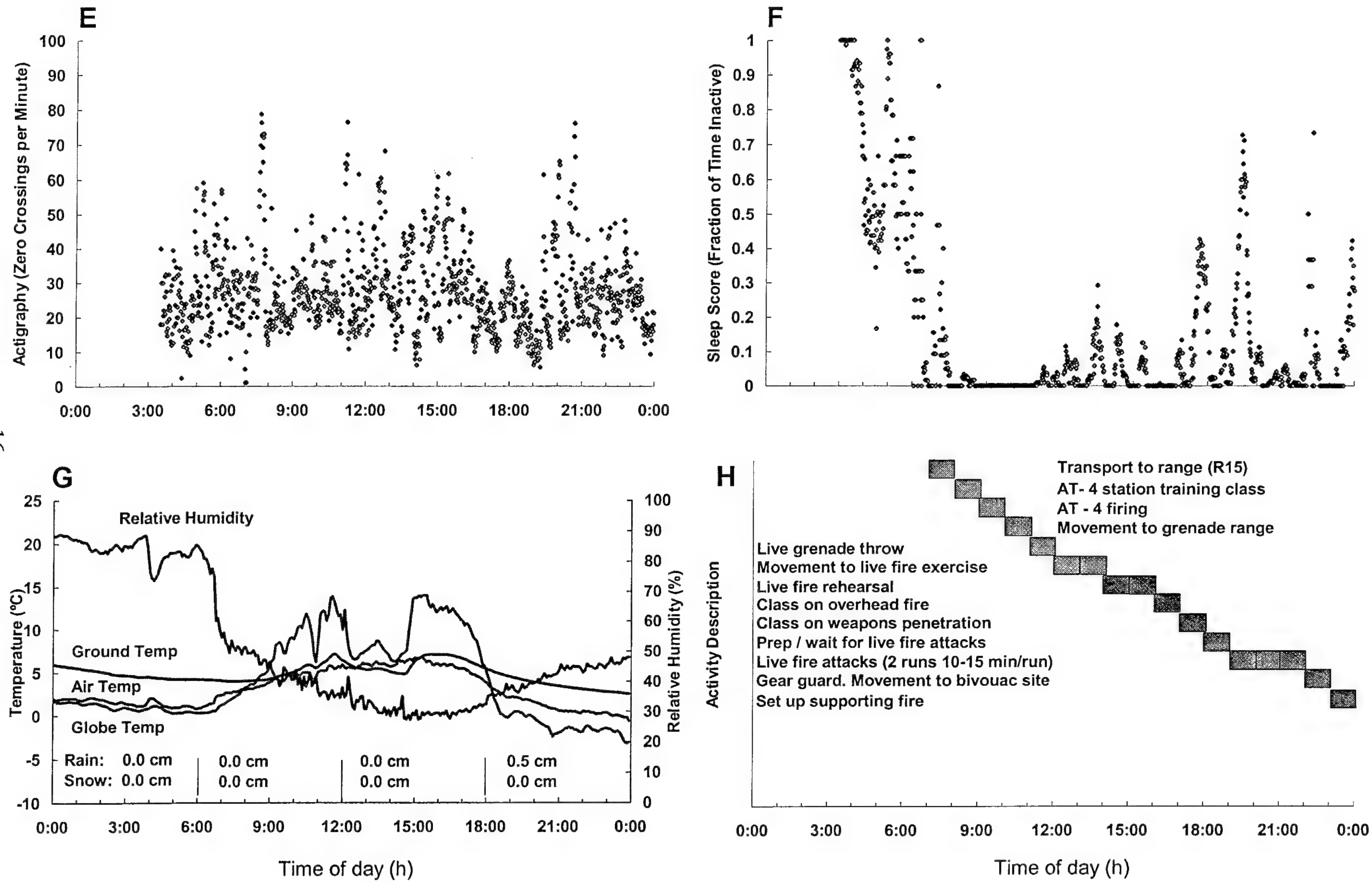
Subj. No.	Ein kcal/d (MJ/d)	CHO (g/d)	Fat (g/d)	Protein (g/d)	Wt. Loss (kg)
1	1206 (5048)	152	51	41	2.9
2	1624 (6798)	196	71	57	--
3	1233 (5161)	150	59	36	4.7
4	1356 (5676)	199	48	39	--
5	1284 (5375)	171	51	41	--
6	1346 (5710)	159	59	47	3.2
7	1278 (5350)	164	52	41	3.1
8	1347 (5639)	170	61	38	5.4
9	1147 (4801)	143	52	32	3.3
10	1161 (4860)	130	54	43	--
11	1016 (4253)	117	45	39	2.9
12	1766 (7392)	228	76	51	2.9
13	1410 (5902)	183	55	50	1.4
14	1487 (6225)	193	62	49	--
Mean	**1333 (5580)**	**168**	**57**	**43**	**3.3**
SD	**196 (820)**	**30**	**9**	**7**	**1.1**

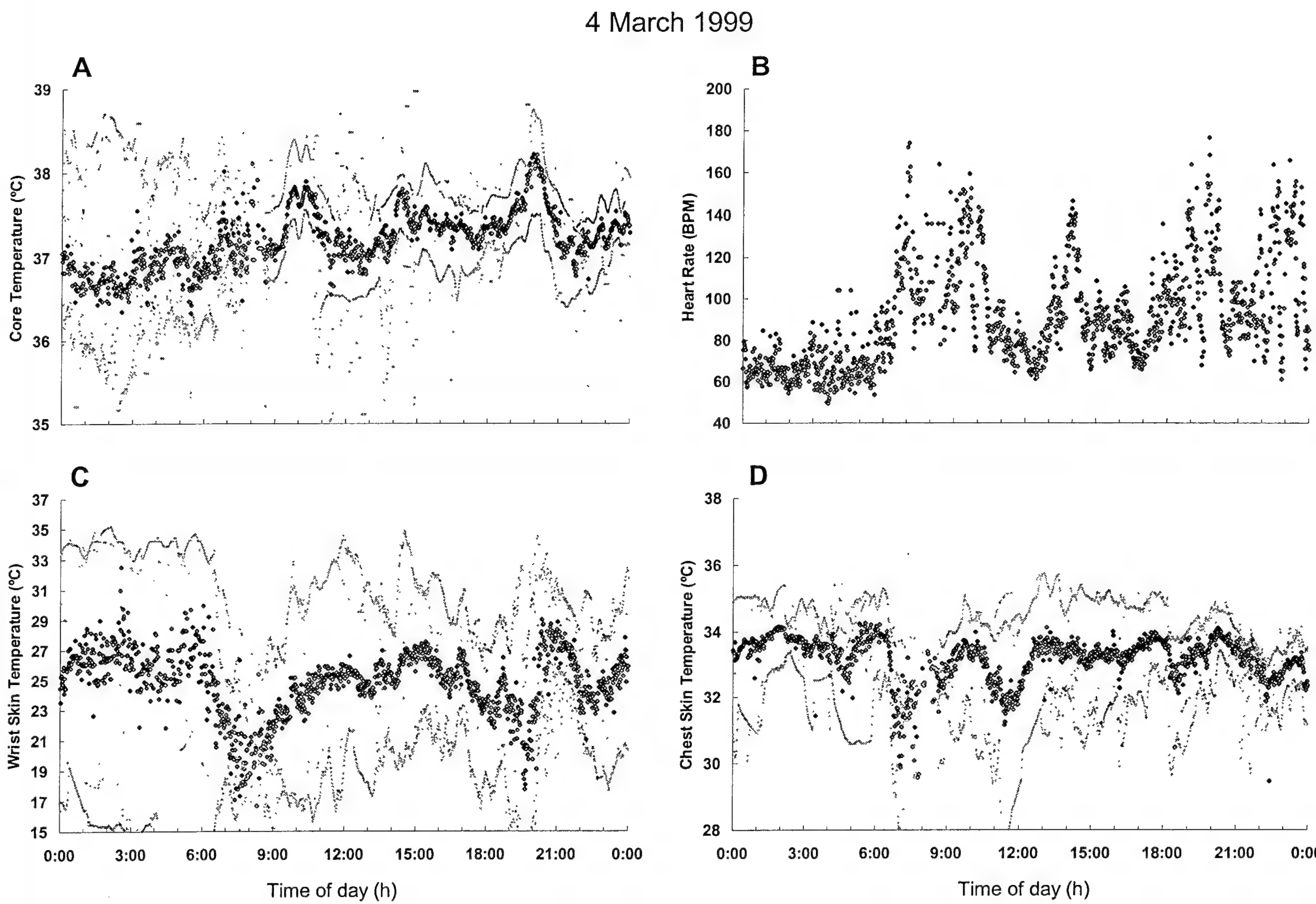
Figure 5. The following pages show physiological, meteorological, and activity data from study Days 1 to 10 (3-12 March 1999). Physiologic parameters shown as means ± range, along with corresponding meteorologic conditions and training activities during each of the 10 training days. Parameters, shown in their respective panels, include (A) core temperature by thermometer pill, (B) heart rate, (C) wrist temperature, (D) chest temperature, (E) actigraphy using a chest mounted sensor (chest motion is expressed as zero crossings per minute), (F) sleep score (a value of 1.0 indicates the individual was inactive, and a value of zero indicates sustained activity over a given 15 min epoch), (G) weather conditions, and (H) field exercise training activities.

3 March 1999

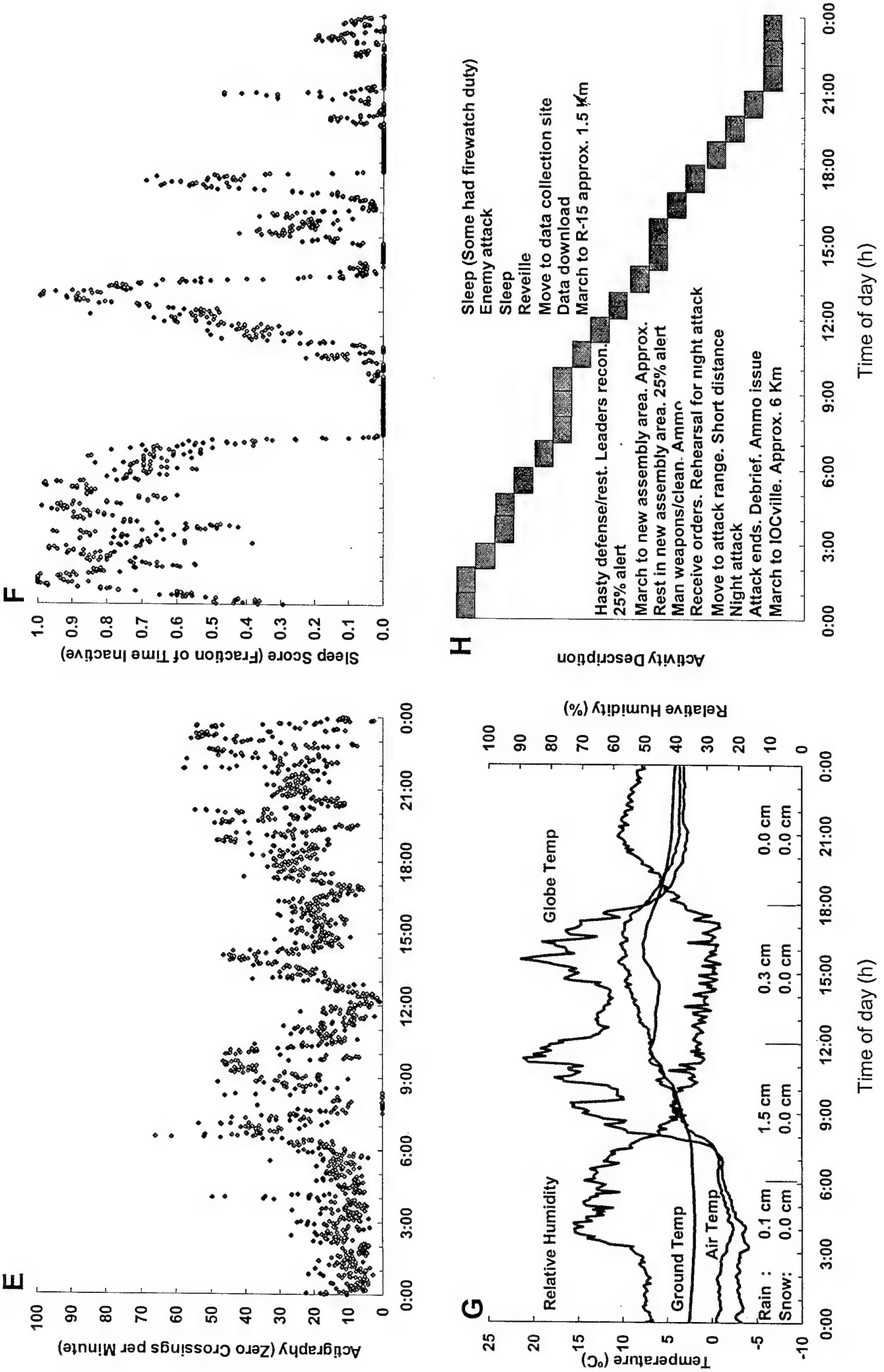


A
Core Temperature (°C)
B
Heart Rate (BPM)
C
Wrist Skin Temperature (°C)
D
Chest Skin Temperature (°C)
Time of day (h)
Time of day (h)

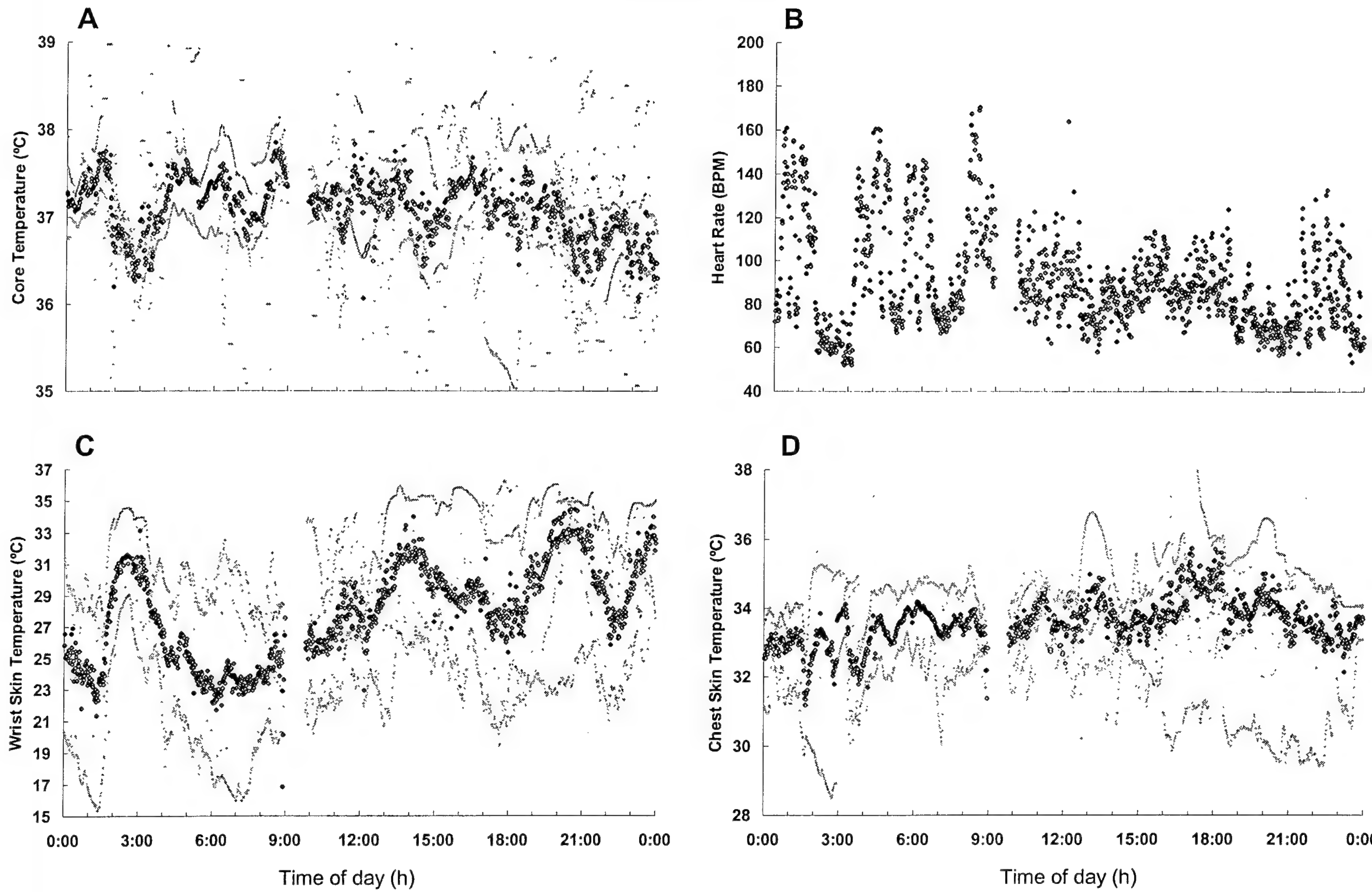

E
Actigraphy (Zero Crossings per Minute)
100
90
80
70
60
50
40
30
20
10
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
F
Sleep Score (Fraction of Time Inactive)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
G
Relative Humidity
Ground Temp
Air Temp
Globe Temp
Temperature (°C)
Relative Humidity (%)
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.5 cm
0.0 cm
Time of day (h)
H
Activity Description
Transport to range (R15)
AT- 4 station training class
AT - 4 firing
Movement to grenade range
Live grenade throw
Movement to live fire exercise
Live fire rehearsal
Class on overhead fire
Class on weapons penetration
Prep / wait for live fire attacks
Live fire attacks (2 runs 10-15 min/run)
Gear guard. Movement to bivouac site
Set up supporting fire
Time of day (h)



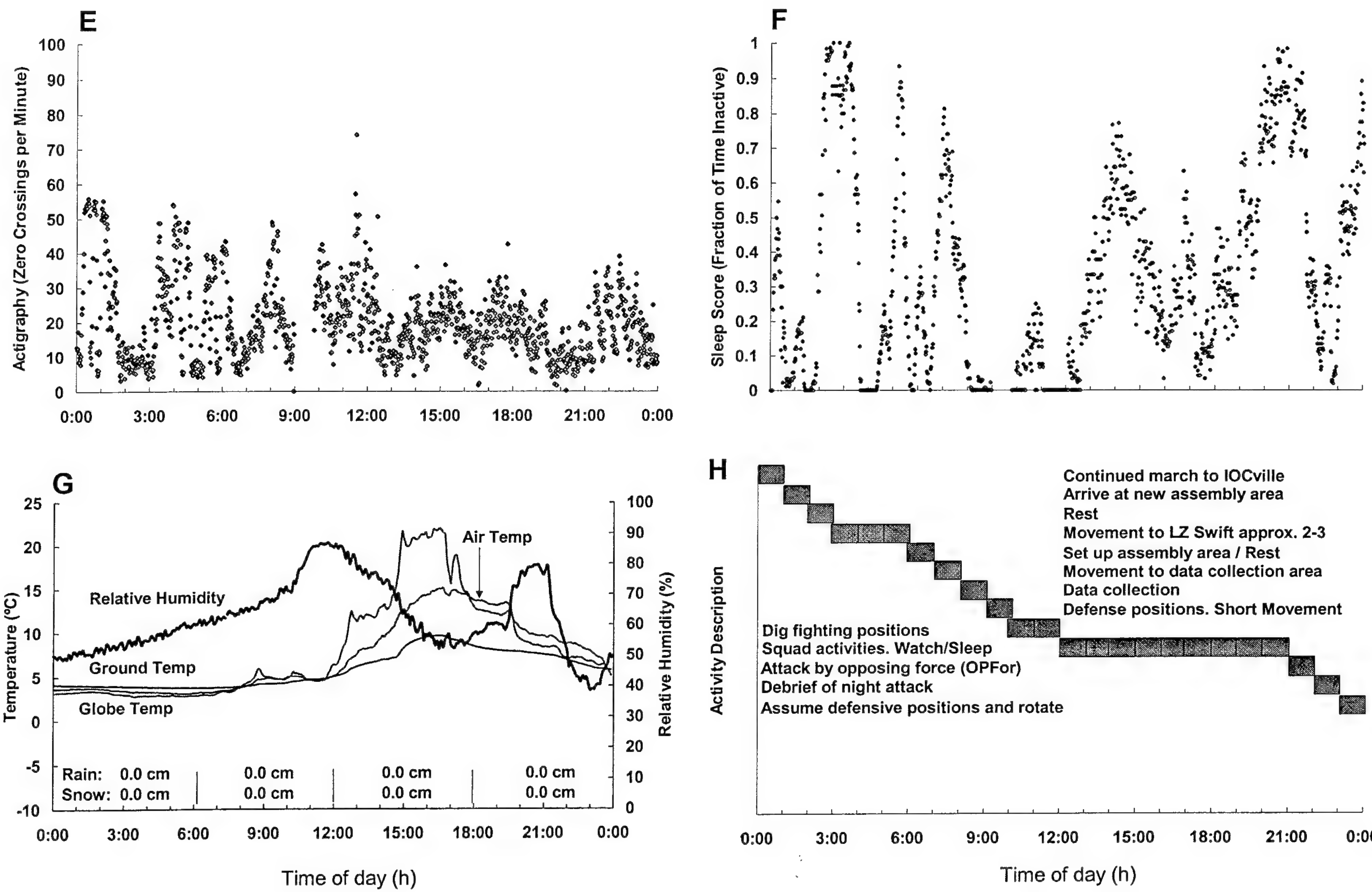
4 March 1999
A
Core Temperature (°C)
39
38
37
36
35
B
Heart Rate (BPM)
200
180
160
140
120
100
80
60
40
C
Wrist Skin Temperature (°C)
37
35
33
31
29
27
25
23
21
19
17
15
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
Time of day (h)
D
Chest Skin Temperature (°C)
38
36
34
32
30
28
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
Time of day (h)


E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Relative Humidity
Globe Temp
Ground Temp
Air Temp
Rain : 0.1 cm 1.5 cm 0.3 cm 0.0 cm
Snow: 0.0 cm 0.0 cm 0.0 cm 0.0 cm
Temperature (°C)
Relative Humidity (%)
Time of day (h)
H
Activity Description
Sleep (Some had firewatch duty)
Enemy attack
Sleep
Reveille
Move to data collection site
Data download
March to R-15 approx. 1.5 Km
Hasty defense/rest. Leaders recon.
25% alert
March to new assembly area. Approx.
Rest in new assembly area. 25% alert
Man weapons/clean. Ammo
Receive orders. Rehearsal for night attack
Move to attack range. Short distance
Night attack
Attack ends. Debrief. Ammo issue
March to IOCville. Approx. 6 Km
Time of day (h)

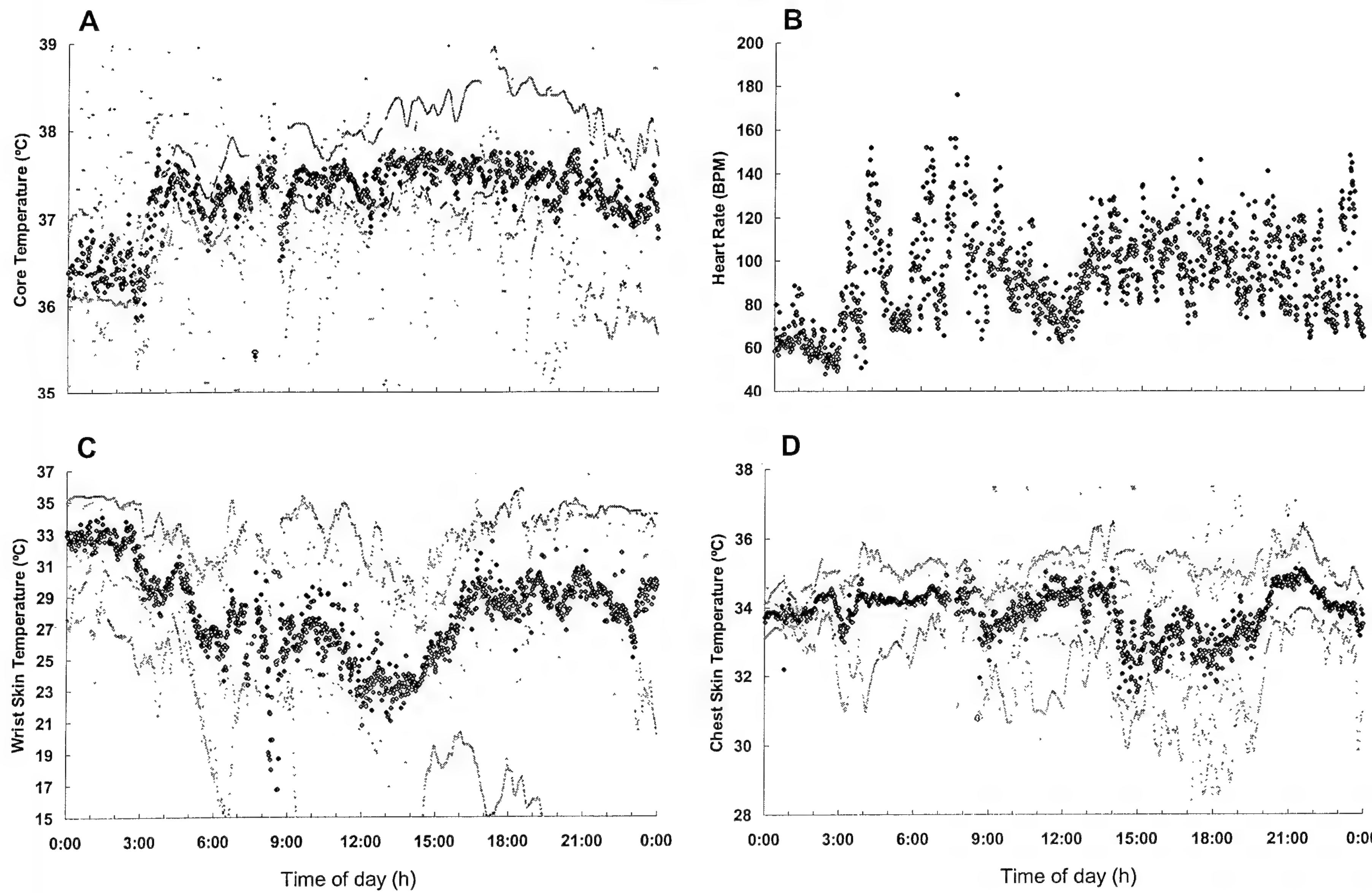
5 March 1999



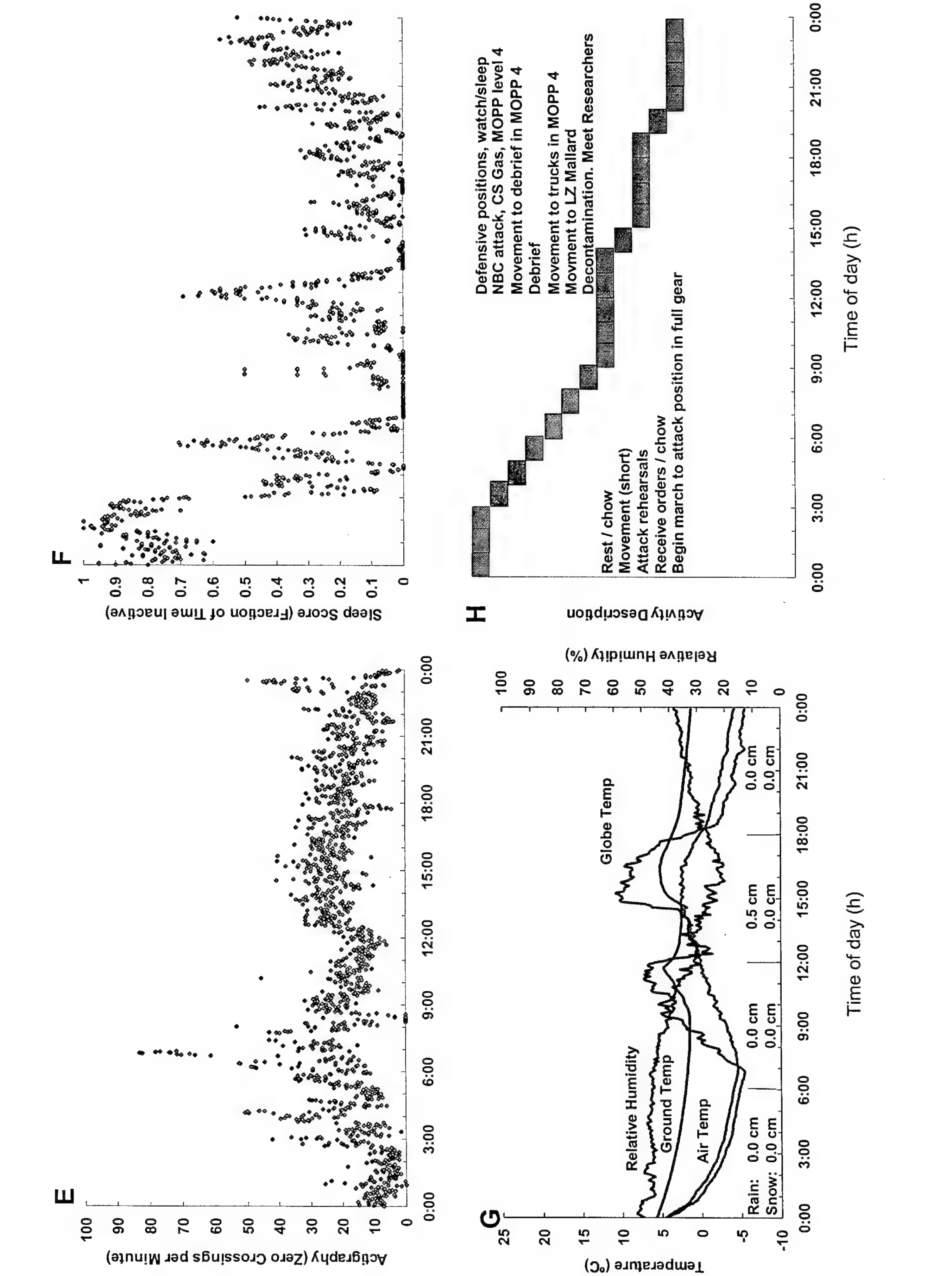
A
B
C
D
Core Temperature (°C)
Heart Rate (BPM)
Wrist Skin Temperature (°C)
Chest Skin Temperature (°C)
Time of day (h)
Time of day (h)


E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Temperature (°C)
Relative Humidity (%)
Relative Humidity
Air Temp
Ground Temp
Globe Temp
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
Time of day (h)
H
Activity Description
Continued march to IOCville
Arrive at new assembly area
Rest
Movement to LZ Swift approx. 2-3
Set up assembly area / Rest
Movement to data collection area
Data collection
Defense positions. Short Movement
Dig fighting positions
Squad activities. Watch/Sleep
Attack by opposing force (OPFor)
Debrief of night attack
Assume defensive positions and rotate
Time of day (h)

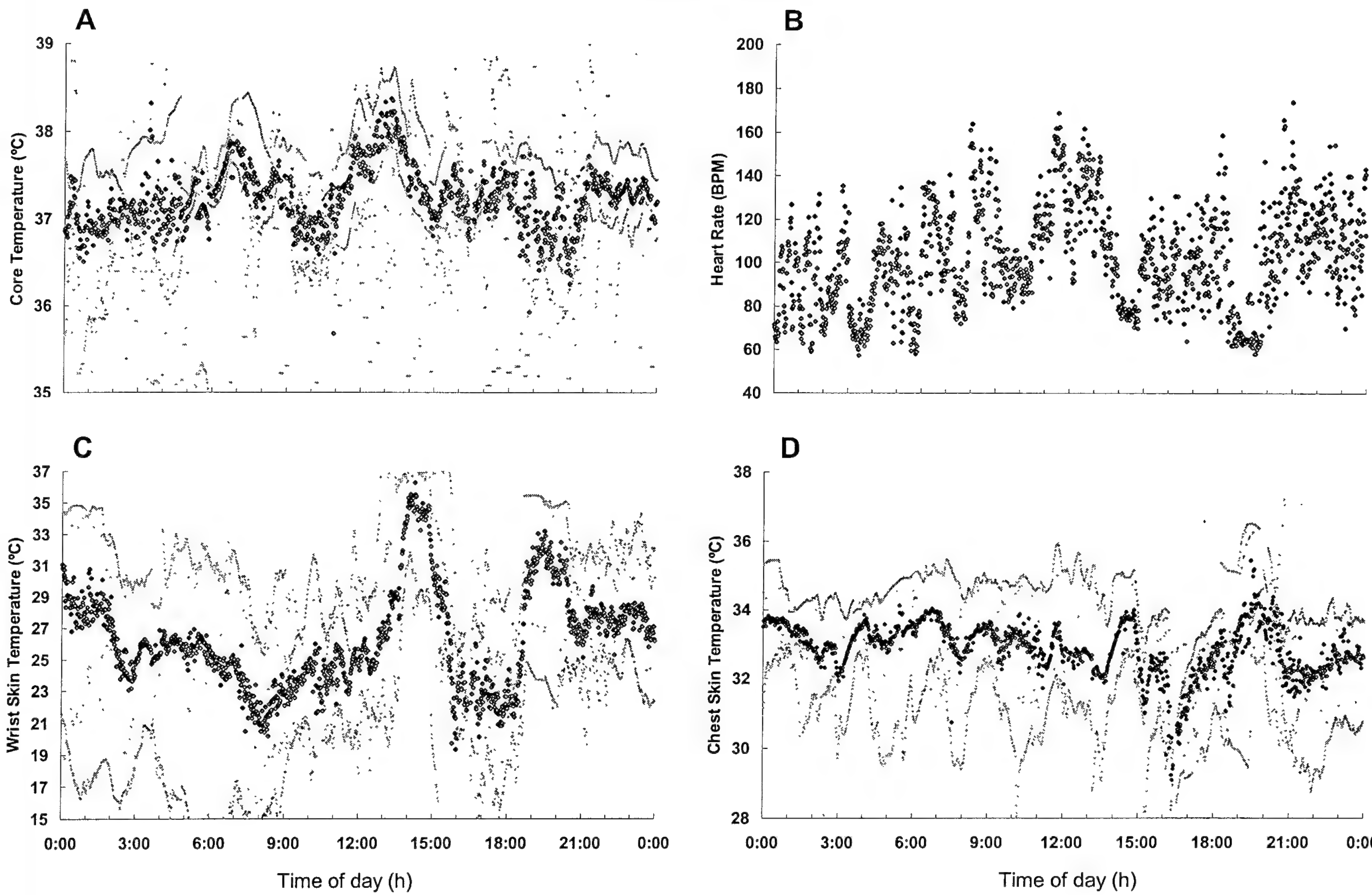
6 March 1999



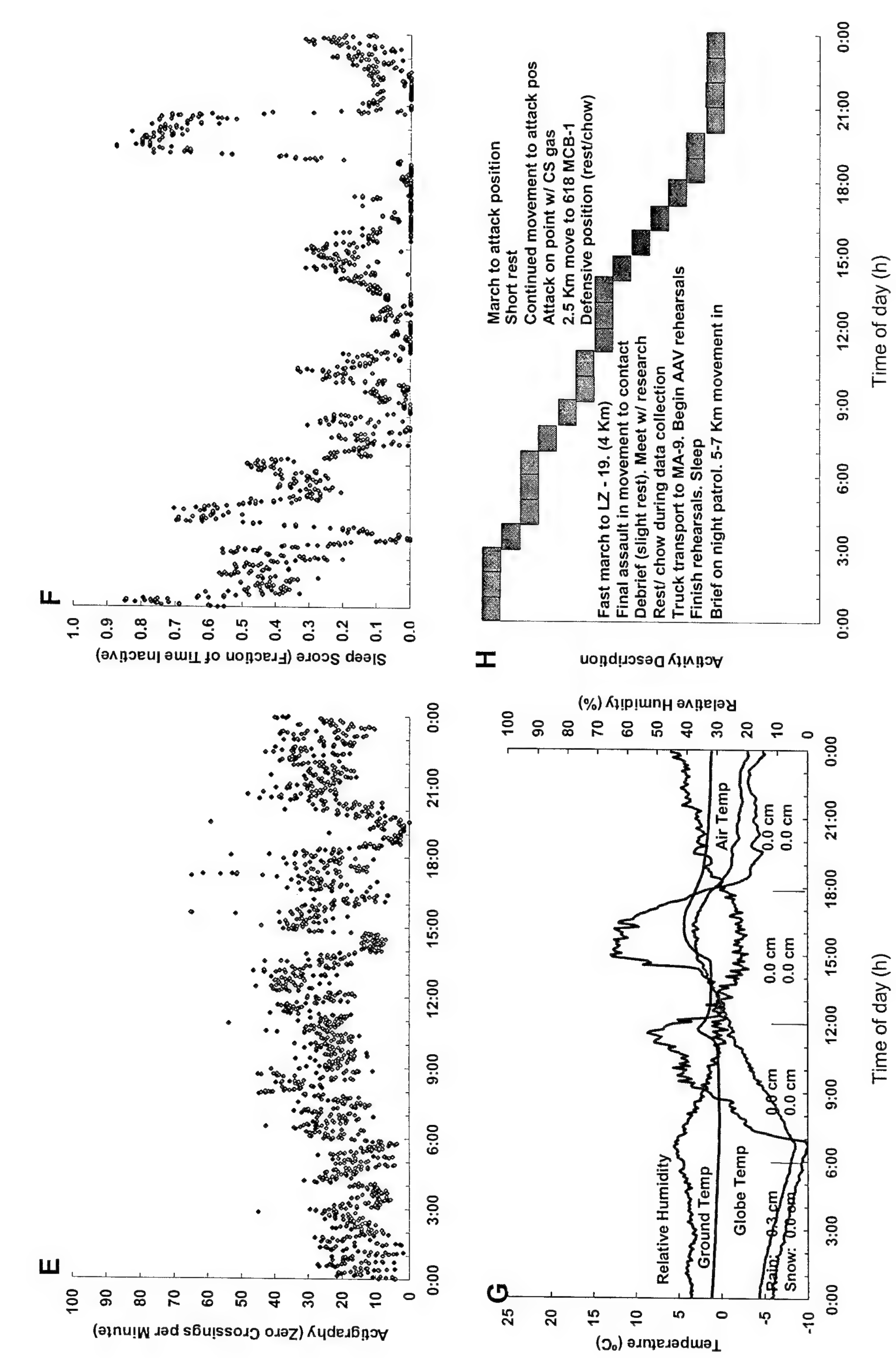
A
Core Temperature (°C)
39
38
37
36
35
B
Heart Rate (BPM)
200
180
160
140
120
100
80
60
40
C
Wrist Skin Temperature (°C)
37
35
33
31
29
27
25
23
21
19
17
15
D
Chest Skin Temperature (°C)
38
36
34
32
30
28
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
Time of day (h)
Time of day (h)


E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Temperature (°C)
Relative Humidity (%)
Relative Humidity
Ground Temp
Air Temp
Globe Temp
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
0.5 cm
0.0 cm
0.0 cm
0.0 cm
H
Activity Description
Rest / chow
Movement (short)
Attack rehearsals
Receive orders / chow
Begin march to attack position in full gear
Defensive positions, watch/sleep
NBC attack, CS Gas, MOPP level 4
Movement to debrief in MOPP 4
Debrief
Movement to trucks in MOPP 4
Movment to LZ Mallard
Decontamination. Meet Researchers
Time of day (h)
Time of day (h)

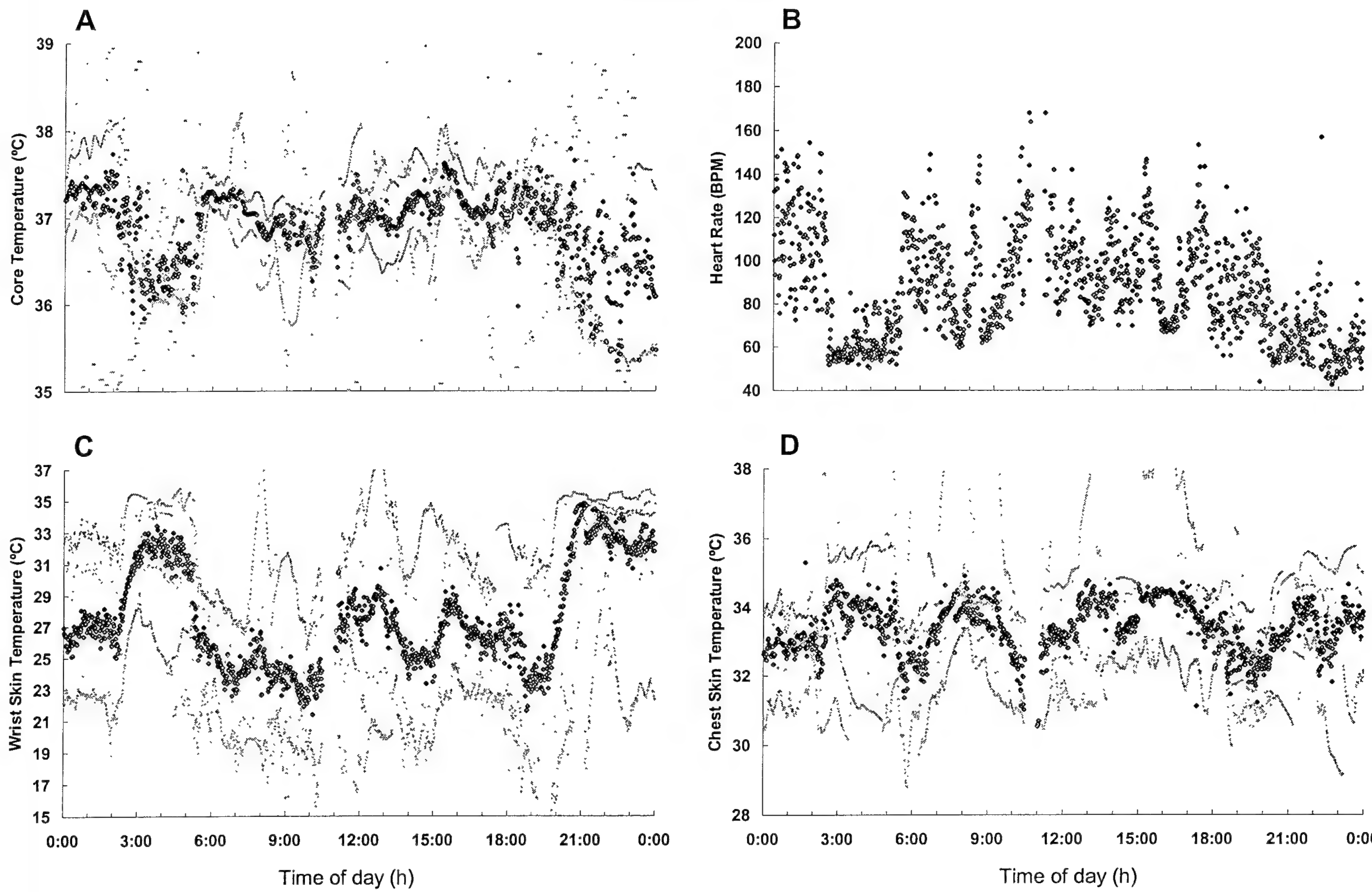
7 March 1999

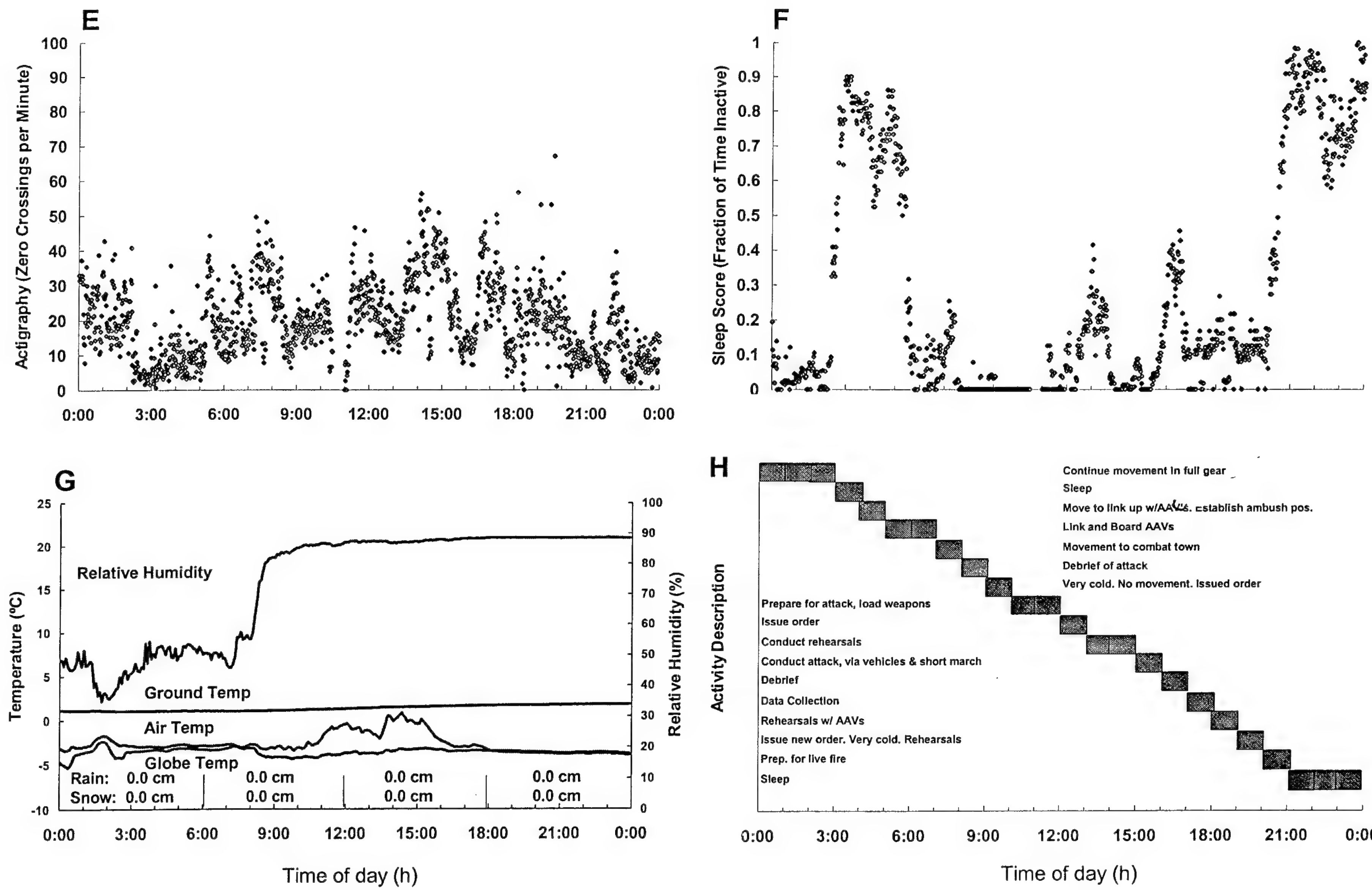


A
Core Temperature (°C)
B
Heart Rate (BPM)
C
Wrist Skin Temperature (°C)
D
Chest Skin Temperature (°C)
Time of day (h)
Time of day (h)


E
Actigraphy (Zero Crossings per Minute)
Time of day (h)
F
Sleep Score (Fraction of Time Inactive)
G
Temperature (°C)
Relative Humidity (%)
Relative Humidity
Ground Temp
Globe Temp
Air Temp
Rain: 0.3 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
Time of day (h)
H
Activity Description
Fast march to LZ - 19. (4 Km)
Final assault in movement to contact
Debrief (slight rest). Meet w/ research
Rest/ chow during data collection
Truck transport to MA-9. Begin AAV rehearsals
Finish rehearsals. Sleep
Brief on night patrol. 5-7 Km movement in
March to attack position
Short rest
Continued movement to attack pos
Attack on point w/ CS gas
2.5 Km move to 618 MCB-1
Defensive position (rest/chow)
Time of day (h)

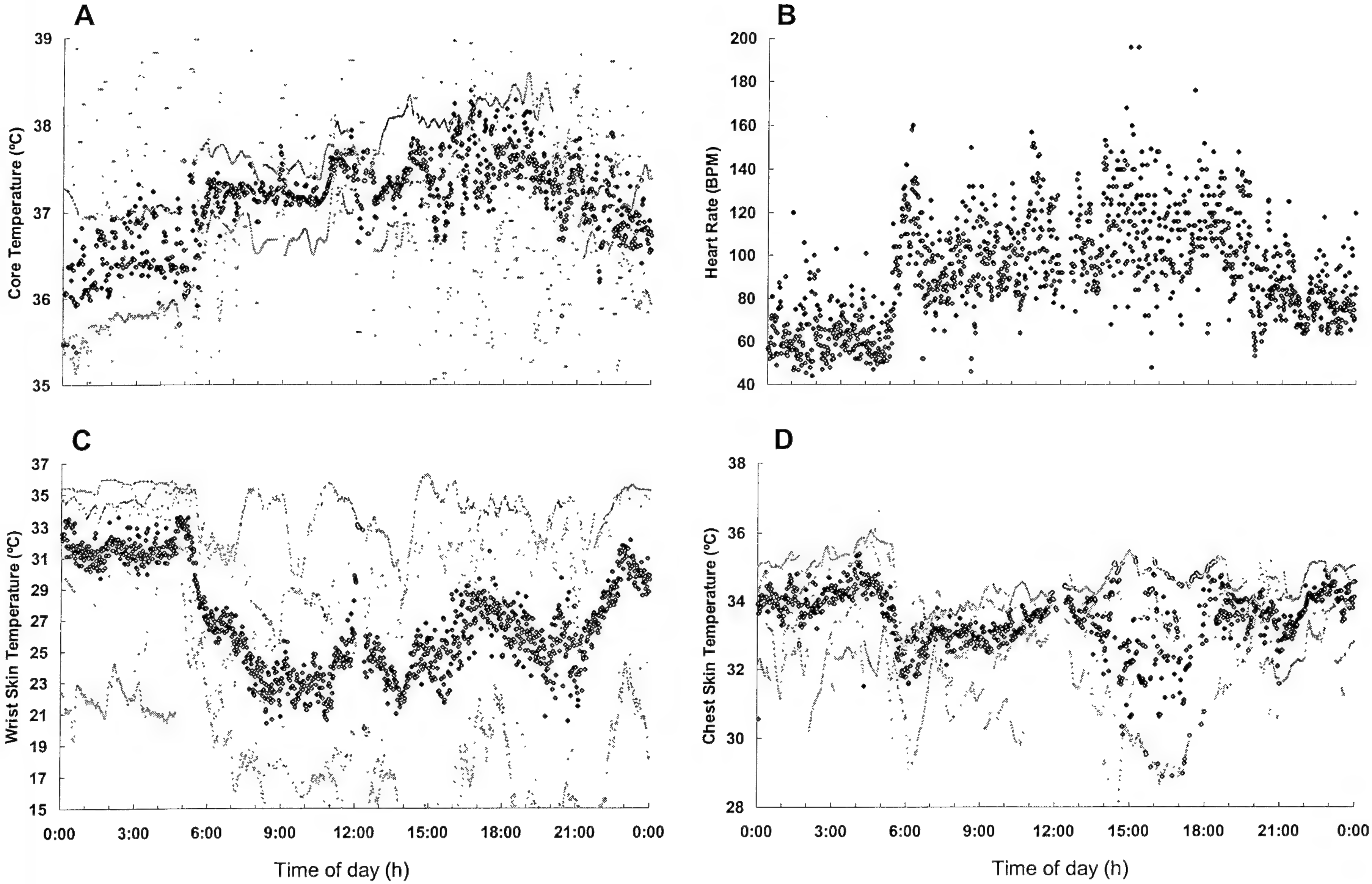
8 March 1999


A
B
C
D
Core Temperature (ºC)
Heart Rate (BPM)
Wrist Skin Temperature (ºC)
Chest Skin Temperature (ºC)
Time of day (h)
Time of day (h)

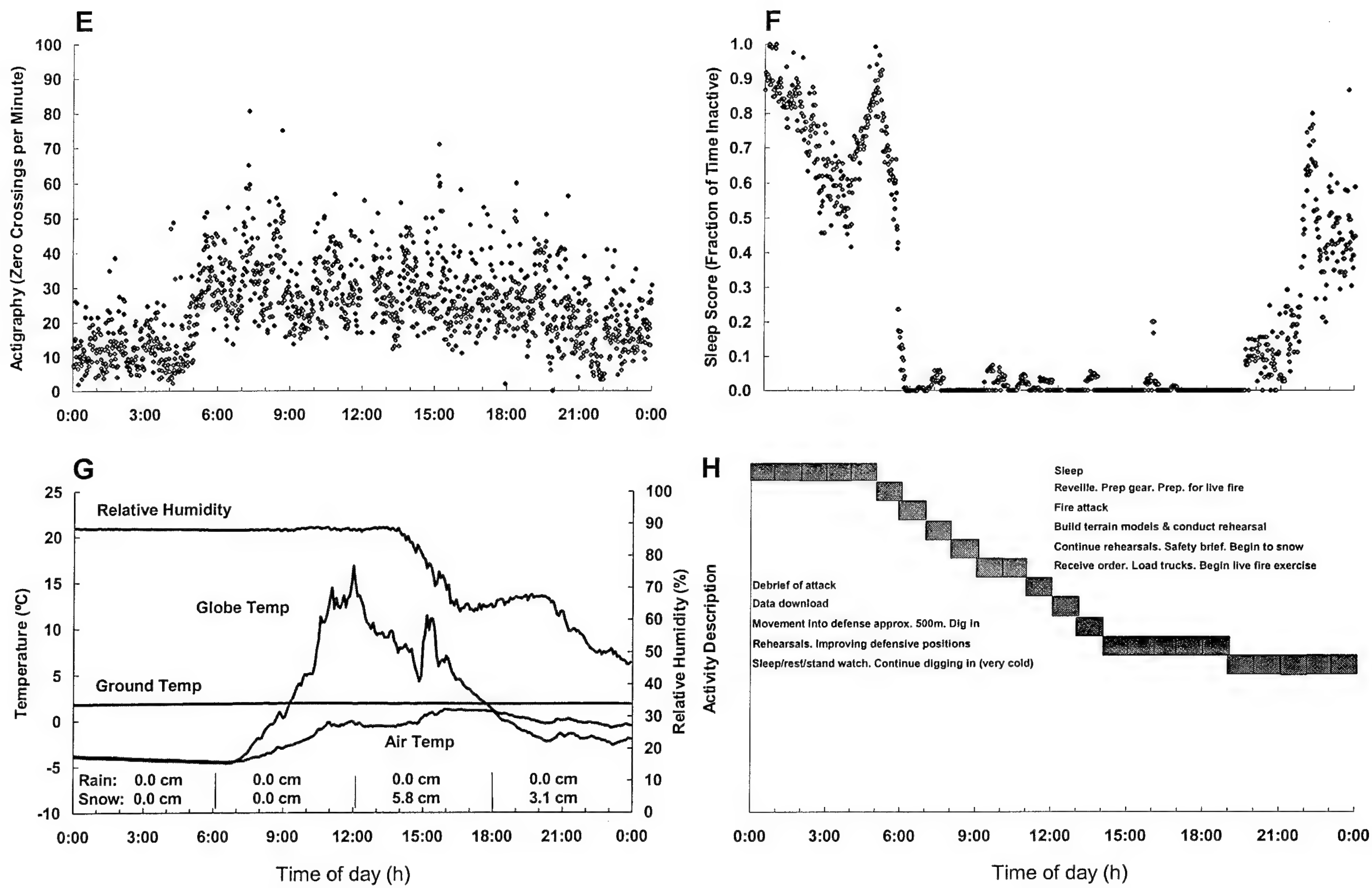


E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Relative Humidity
Ground Temp
Air Temp
Globe Temp
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
0.0 cm
Temperature (°C)
Relative Humidity (%)
Time of day (h)
H
Activity Description
Continue movement in full gear
Sleep
Establish ambush pos.
Link and Board AAVs
Movement to combat town
Debrief of attack
Very cold. No movement. Issued order
Prepare for attack, load weapons
Issue order
Conduct rehearsals
Conduct attack, via vehicles & short march
Debrief
Data Collection
Rehearsals w/ AAVs
Issue new order. Very cold. Rehearsals
Prep. for live fire
Sleep
Time of day (h)

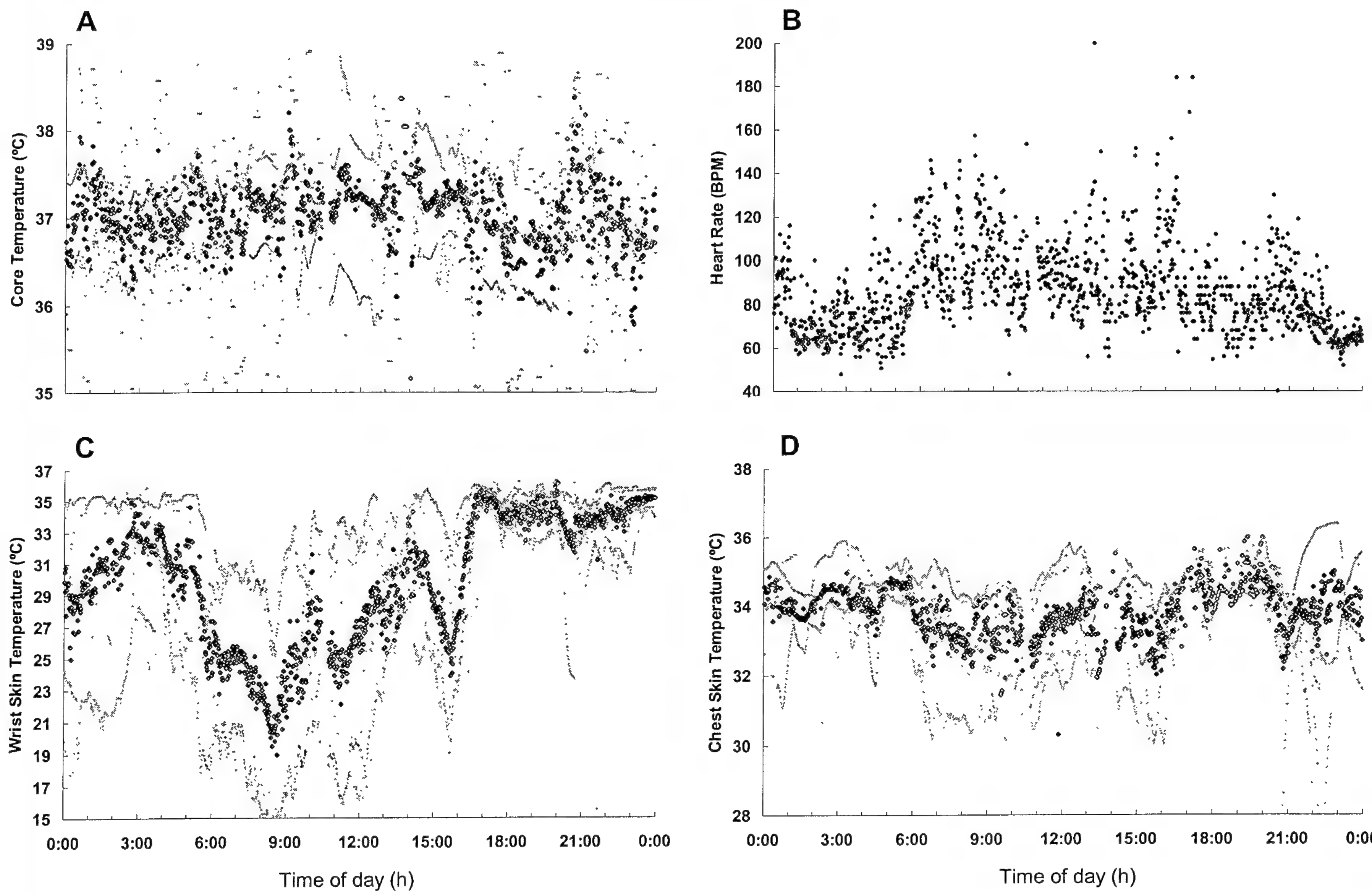
9 March 1999

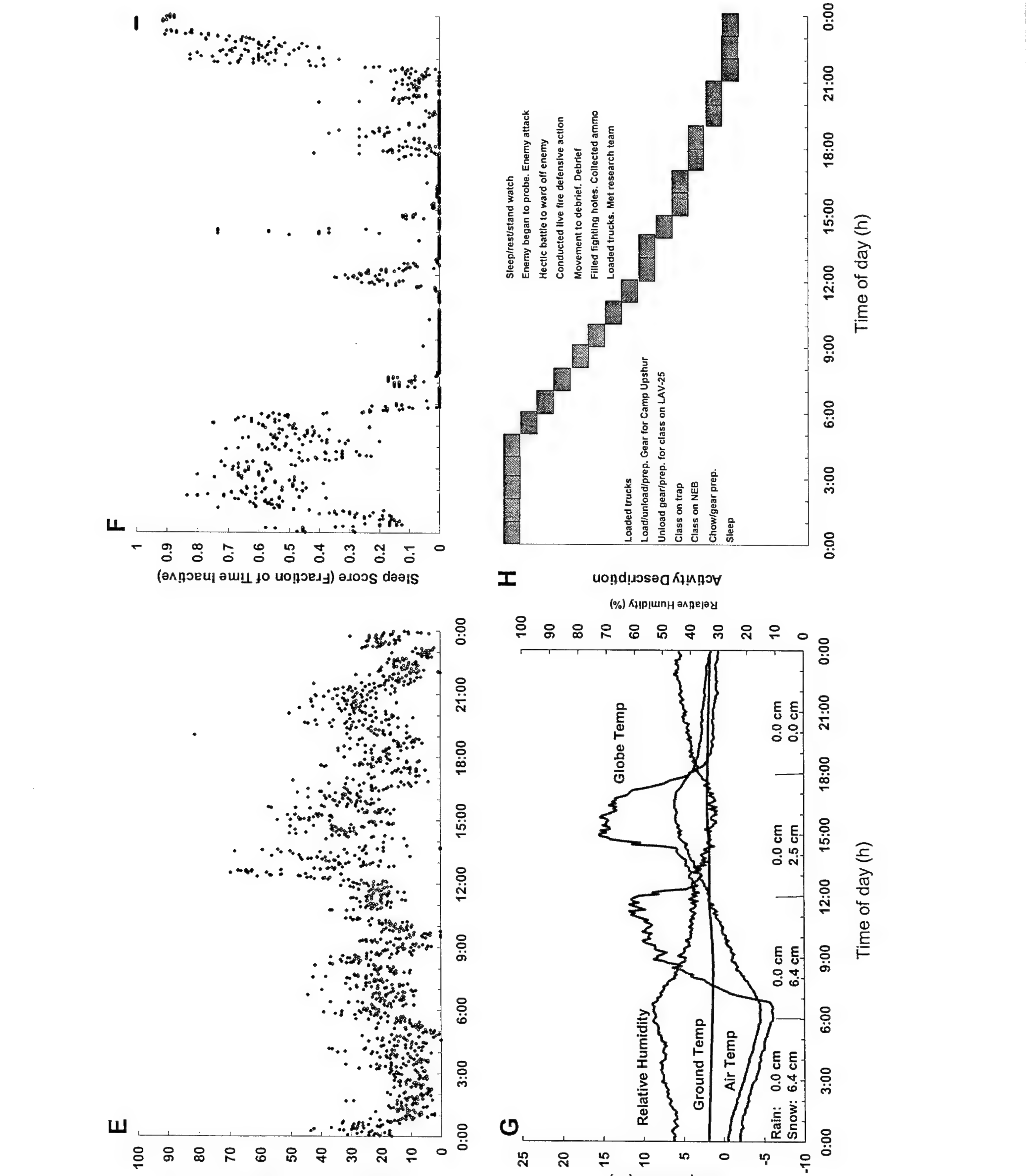


A
Core Temperature (ºC)
B
Heart Rate (BPM)
C
Wrist Skin Temperature (ºC)
Time of day (h)
D
Chest Skin Temperature (ºC)
Time of day (h)

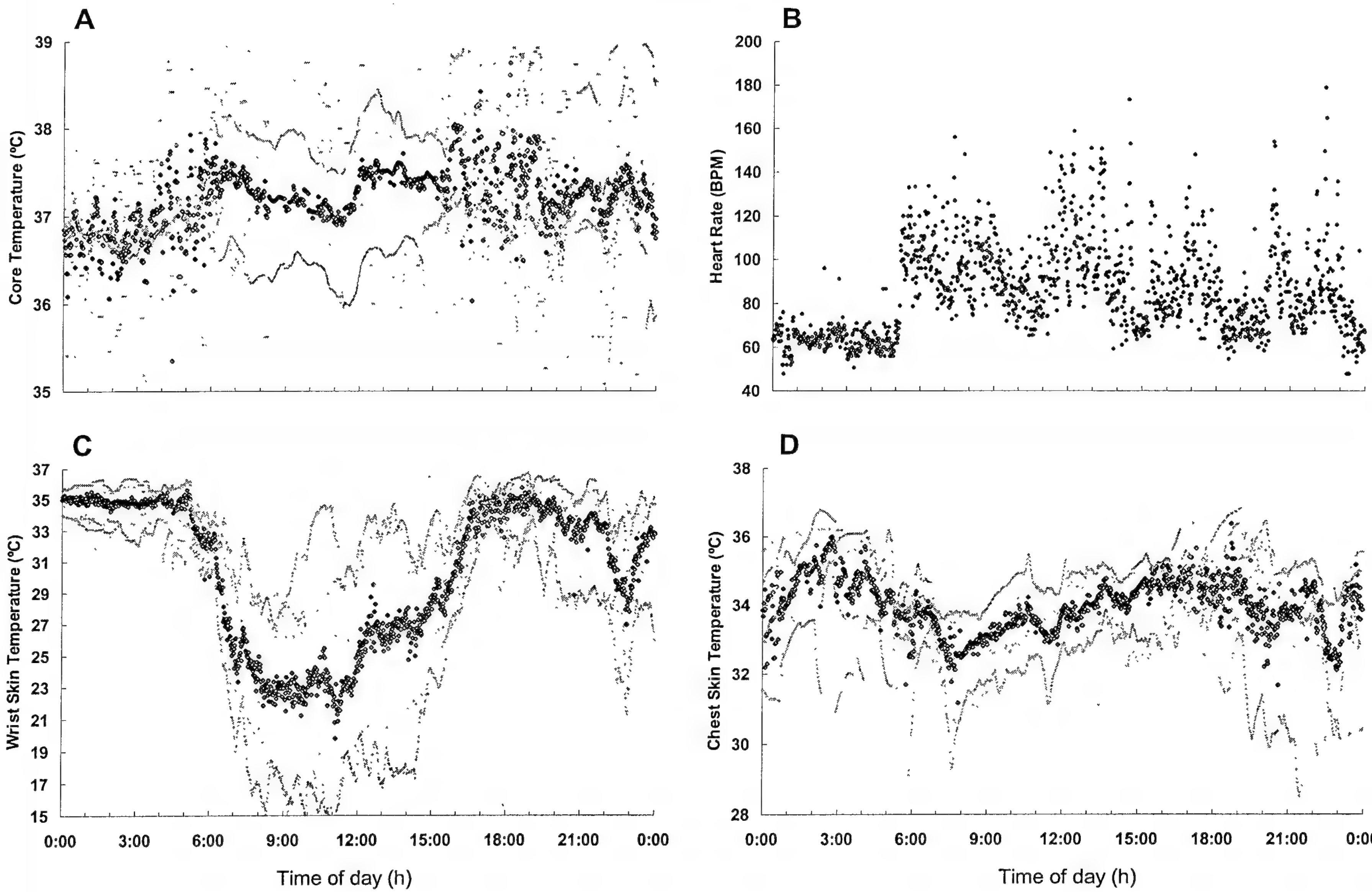

E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Relative Humidity
Globe Temp
Ground Temp
Air Temp
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
0.0 cm
5.8 cm
0.0 cm
3.1 cm
Temperature (°C)
Relative Humidity (%)
Time of day (h)
H
Activity Description
Sleep
Reveille. Prep gear. Prep. for live fire
Fire attack
Build terrain models & conduct rehearsal
Continue rehearsals. Safety brief. Begin to snow
Receive order. Load trucks. Begin live fire exercise
Debrief of attack
Data download
Movement into defense approx. 500m. Dig in
Rehearsals. Improving defensive positions
Sleep/rest/stand watch. Continue digging in (very cold)
Time of day (h)

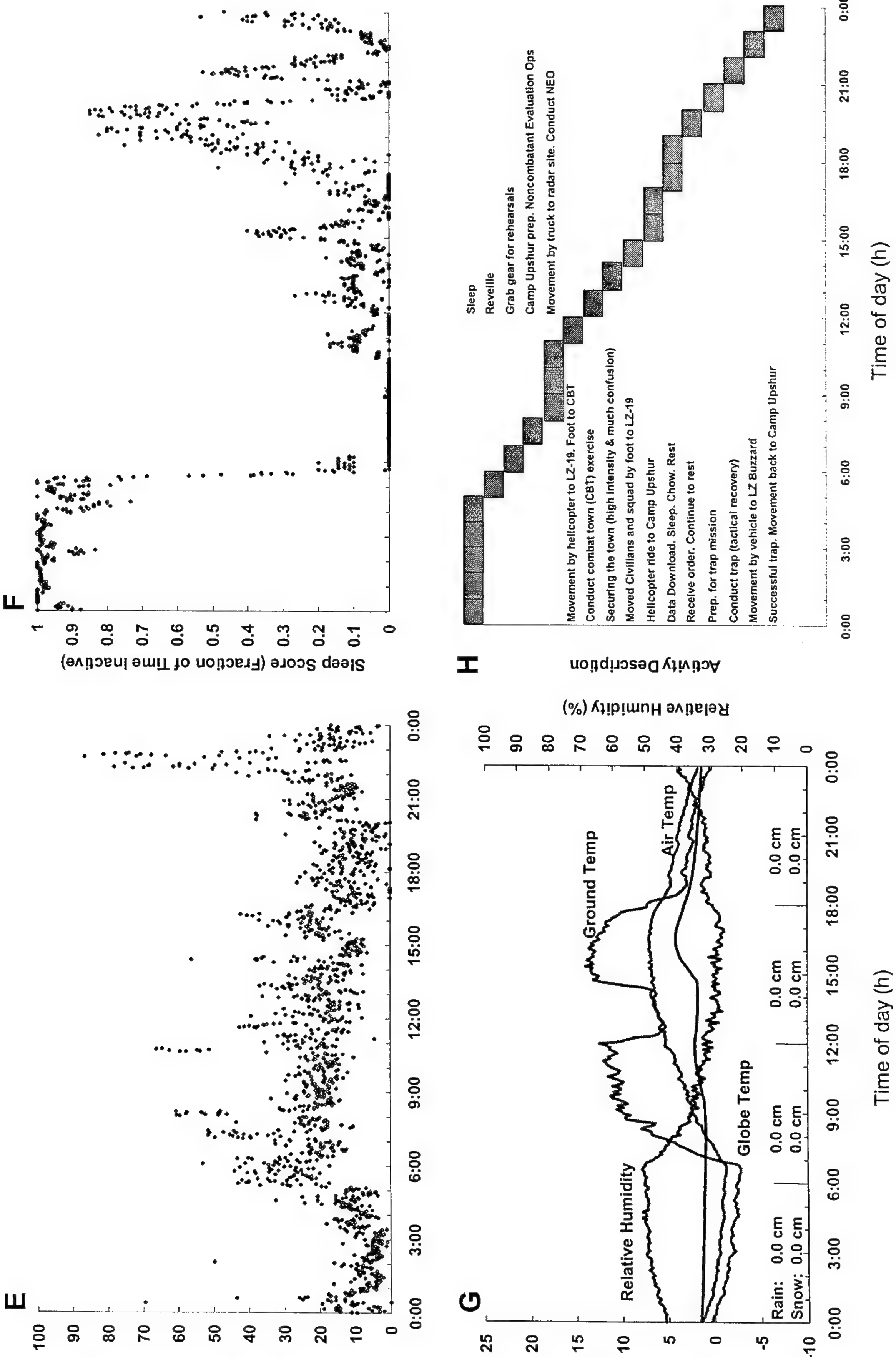
10 March 1999




E
F
G
H
I
Actigraphy (Zero Crossings per Minute)
Sleep Score (Fraction of Time Inactive)
Temperature (°C)
Relative Humidity (%)
Activity Description
Time of day (h)
Relative Humidity
Ground Temp
Air Temp
Globe Temp
Rain: 0.0 cm
Snow: 6.4 cm
0.0 cm
6.4 cm
0.0 cm
2.5 cm
0.0 cm
0.0 cm
Loaded trucks
Load/unload/prep. Gear for Camp Upshur
Unload gear/prep. for class on LAV-25
Class on trap
Class on NEB
Chow/gear prep.
Sleep
Sleep/rest/stand watch
Enemy began to probe. Enemy attack
Hectic battle to ward off enemy
Conducted live fire defensive action
Movement to debrief. Debrief
Filled fighting holes. Collected ammo
Loaded trucks. Met research team

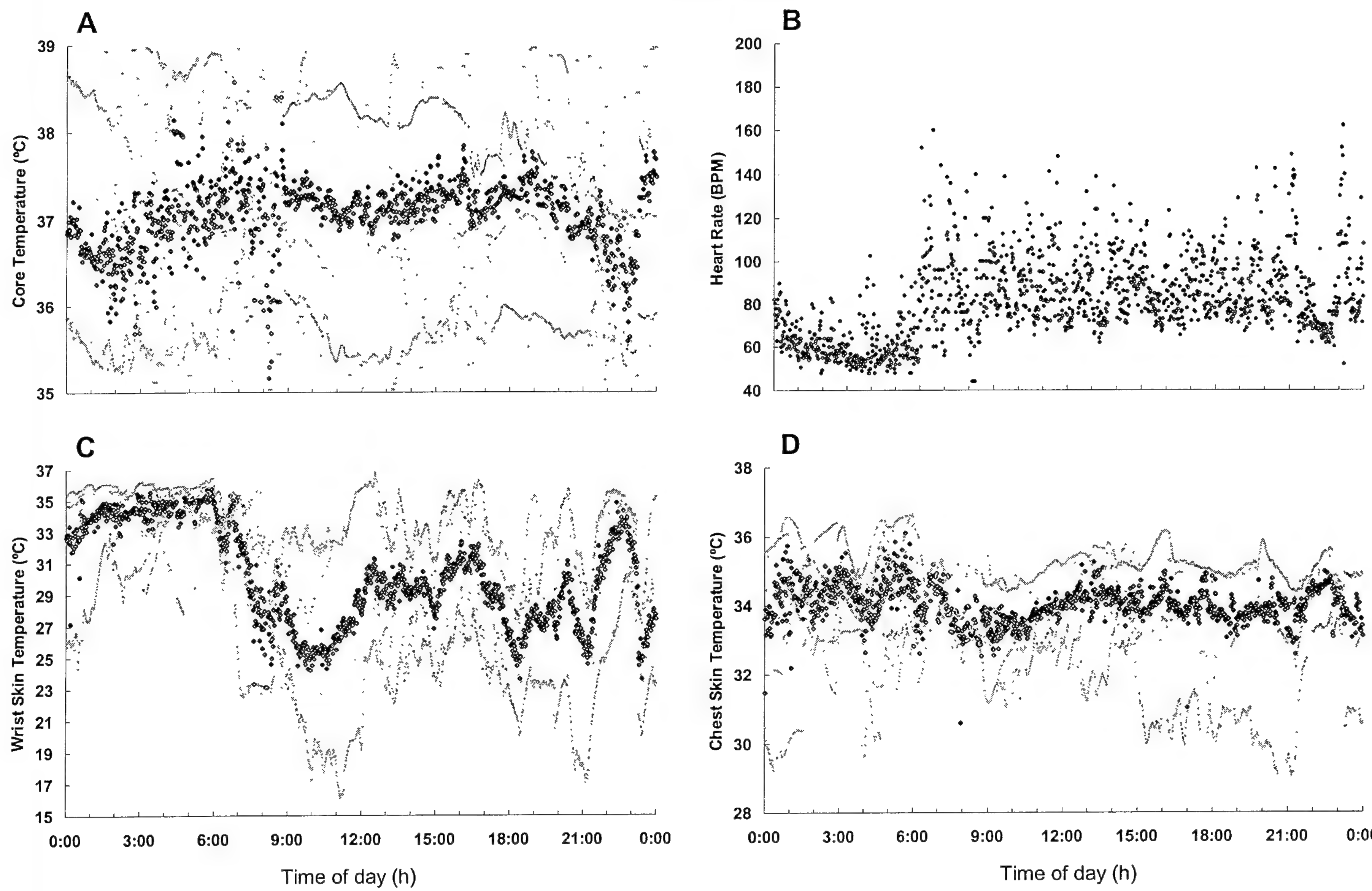
11 March 1999





E
Actigraphy (Zero Crossings per Minute)
Time of day (h)
F
Sleep Score (Fraction of Time Inactive)
G
Temperature (°C)
Relative Humidity (%)
Relative Humidity
Ground Temp
Air Temp
Globe Temp
Rain: 0.0 cm
Snow: 0.0 cm
Time of day (h)
H
Activity Description
Sleep
Reveille
Grab gear for rehearsals
Camp Upshur prep. Noncombatant Evaluation Ops
Movement by truck to radar site. Conduct NEO
Movement by helicopter to LZ-19. Foot to CBT
Conduct combat town (CBT) exercise
Securing the town (high intensity & much confusion)
Moved Civilians and squad by foot to LZ-19
Helicopter ride to Camp Upshur
Data Download. Sleep. Chow. Rest
Receive order. Continue to rest
Prep. for trap mission
Conduct trap (tactical recovery)
Movement by vehicle to LZ Buzzard
Successful trap. Movement back to Camp Upshur
Time of day (h)

12 March 1999



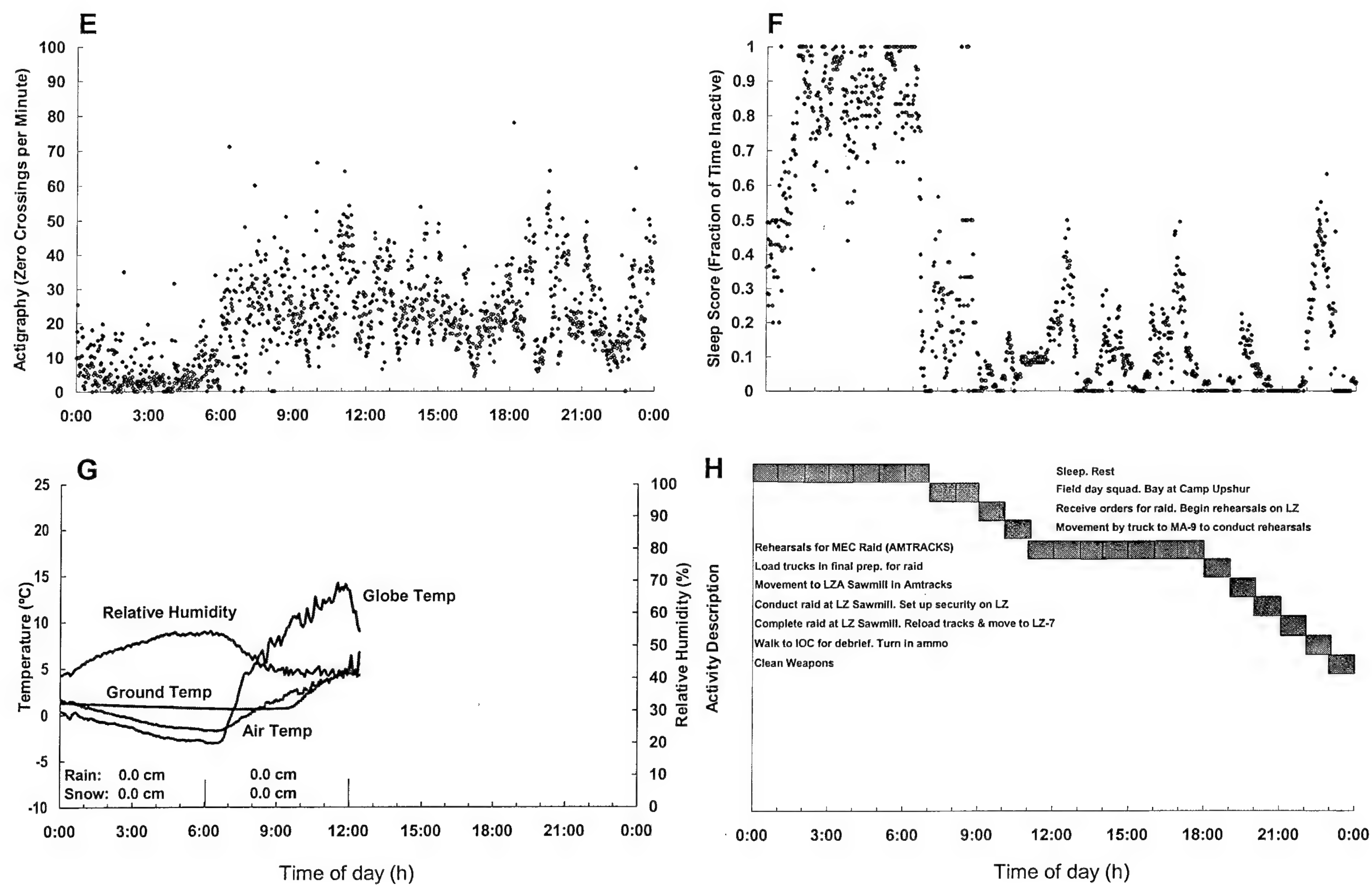

E
Actigraphy (Zero Crossings per Minute)
F
Sleep Score (Fraction of Time Inactive)
G
Temperature (ºC)
Relative Humidity (%)
Relative Humidity
Globe Temp
Ground Temp
Air Temp
Rain: 0.0 cm
Snow: 0.0 cm
0.0 cm
0.0 cm
Time of day (h)
H
Activity Description
Sleep. Rest
Field day squad. Bay at Camp Upshur
Receive orders for raid. Begin rehearsals on LZ
Movement by truck to MA-9 to conduct rehearsals
Rehearsals for MEC Raid (AMTRACKS)
Load trucks in final prep. for raid
Movement to LZA Sawmill in Amtracks
Conduct raid at LZ Sawmill. Set up security on LZ
Complete raid at LZ Sawmill. Reload tracks & move to LZ-7
Walk to IOC for debrief. Turn in ammo
Clean Weapons
Time of day (h)

Table 4. List of field exercise activities associated with heart rates >140 beats per minute.

Day	Start Time (h)	Duration (min)	Activity	HR (bpm)	N	Max	Min	% of period ≥140 bpm
1	14:50	13	Rehearsal (live fire)	140± 9	11	150	124	54
	19:44	15	Attack (live fire exercise)	145±16	10	163	106	80
	20:27	18	Attack (live fire exercise #2)	148±13	10	163	122	72
2	9:02	44	Movement	130±17	6	159	94	32
	18:48	29	Attack	127±17	4	164	86	21
	22:56	50	Movement	126±22	8	166	83	30
3	0:14	62	Movement (cont. from d 2)	124±27	7	161	70	35
	3:54	45	Movement to LZ Swift (pre-break)	129±24	8	161	74	40
	5:31	38	Movement to LZ Swift (post-break)	116±27	10	146	68	21
	7:48	33	Movement	135±21	8	170	98	42
4	3:45	30	Attack (NBC)	125±12	7	152	96	10
	6:07	22	Movement	126±19	7	152	84	27
	23:21	16	Movement (start)	130±11	9	148	108	25
5	7:45	70	Attack (on entrenched position)	124±22	9	164	84	27
	11:06	130	Movement (fast paced, to LZ 19)	133±17	7	169	91	45
	18:02	20	Rehearsal	116±22	5	159	73	20
	20:45	31	Patrol (night)	129±16	4	174	104	16
6	0:00	129	Movement (full gear)	112±20	6	154	73	11
	15:20	22	Attack (via vehicles)	124±13	7	147	95	18
7	5:26	41	Attack (live fire exercise)	121±15	3	160	86	7
	10:38	30	Attack (live fire exercise)	124±20	4	157	80	20
8	5:57	159	Battle (hectic, with movement)	104±19	4	157	70	4
9	11:37	15	Movement (by helicopter)	128±12	4	147	102	20
	12:06	91	Attack (secure town)	111±20	5	159	78	4

N = subject number

Metabolic cost of marching

The estimated metabolic cost of a 4.15 km night movement over rolling terrain (% grade = 0 to 4.9%)(day 4 to 5) was calculated by the Pandolf equation (56) using GPS data from one squad member with good GPS data and assuming a body weight of 81 kg and a load weight of 49 kg. During the half hour associated with the highest rates of movement, heart rate averaged 130±11 bpm (range = 108-148 bpm)(n=9). The total metabolic energy expended in marching was about 1260 kcal (5274 kJ), and movement velocity averaged 0.3 ms^{-1} (range = 0.11 to 0.76 ms^{-1})(to convert ms^{-1} to mph, multiply by 2.237)(Table 5).

Table 5. Night march to attack position in full gear (day 4 to 5). Total distance traversed was 4.15 km, at an average velocity of 0.19 m/sec or 0.43 mph (range = 0.012 to 0.761 ms^{-1}; 0.03 to 1.7 mph), with a total energy expenditure during the 6 hour period of about 1260 kcal (5274 kJ) as calculated by the Pandolf equation assuming a body weight of 81 kg and a load of 49 kg.

Time (EST)	Latitude	Longitude	Distance Traversed (m)	Grade (%)	Velocity (ms^{-1})	Velocity (mph)	Energy Expenditure (W)	Energy Expenditure (kcal/min)
19:00	38.5482	-77.4267	---	---	---	---	---	---
19:30	38.5484	-77.4265	31	0	0.017	0.04	216	3.1
20:00	38.5485	-77.4267	22	0	0.012	0.03	216	3.1
20:30	38.5527	-77.4289	507	0	0.282	0.63	234	3.4
21:00	38.5549	-77.4297	250	0	0.139	0.31	220	3.2
21:30	38.5570	-77.4320	303	4.9	0.169	0.38	267	3.8
22:00	38.5587	-77.4323	200	2.5	0.11	0.25	234	3.4
22:30	38.5616	-77.4350	392	2.6	0.218	0.49	257	3.7
23:00	38.5618	-77.4357	68	0	0.038	0.09	216	3.1
23:30	38.5706	-77.4467	1370	0.7	0.761	1.70	381	5.5
0:00	38.5739	-77.4511	529	0	0.294	0.66	236	3.4
0:30	38.5736	-77.4514	38	0	0.021	0.05	216	3.1
1:00	38.5776	-77.4507	443	0	0.246	0.55	230	3.3

DISCUSSION

ENERGY BALANCE

How Much Metabolic Energy Did The Marines Expend During TheirField Exercise?

The physical demands of load carriage by infantry are known to be substantial (24). The high TDEEs of the Marines during their winter IOC FEX (5380±680 kcal/d)(22.52±2.85 MJ/d) are similar to those recorded during (a) small unit winter combat training course at the U.S.

Marine Corps Mountain Warfare Training Center, Bridgeport, CA (29), and (b) field training by Rangers (1st Battalion, 75th Ranger Regiment) (71). Examples of higher TDEEs include those of Norwegian Ranger Cadets during a week of sustained physical activity and sleep deprivation (26,55), and Tour de France cyclists (typical TDEE = 6070±335 kcal/d (25.41±1.4 MJ/d), peak TDEE = 7815±380 kcal/d (32.71±1.40 MJ/d); n = 4, 21 d study duration)(61). When energy expenditure is expressed relative to resting metabolic rate, that is, expressed as the ratio of TDEE/RMR, the IOC Marines averaged 2.8 (range = 2.5–3.0), while Tour de France cyclists ranged from about 4–5. The high TDEEs in the present study reflect the high energetic cost of carrying heavy loads, the large fraction of the day spent in physical activity, and the high intensity of activities such as attacks on objectives and long-distance movements.

<u>What Activities Were Associated With The Highest Rates Of Energy Expenditure?</u>

Using heart rate as an index of physical activity, it was clear that movements and attacks were particularly demanding, commonly being associated with heart rates in excess of 140 beats per min (Table 4). The duration of movements (mean = 51 min; range = 16 to 130 min) and attacks (mean = 37 min; range = 13 to 91 min) were similar. Exercise intensity was also similar for movements (mean HR = 126; range = 112 to 123) and attacks (mean HR = 126; range = 104 to 148). Less common activities, such as offensive military operations in urban terrain (MOUT) and establishing defensive positions (digging in), were also physically demanding.

The energy costs of a night march were calculated from GPS data and estimated load using the Pandolf equation (Table 5)(56). These calculated values are conservative in that no correction was made for the tendency of the Pandolf equation to underestimate the metabolic cost of prolonged walking with an external load by about 10%–16% (57). The rates of energy expenditure (3.1 to 5.5 kcal/min)(13 to 23 kJ/min) were similar to those reported by Goldman (23), equal to 44%–78% of the estimated 425 kcal/h (1.8 MJ/h) maximum sustainable exercise intensity for soldiers engaged in realistic combat activities (33). Rates of movement (0.02 to 0.8 ms^{-1}) were also similar to those reported by Hughes and Goldman (33)(see review by Haisman, 1988 [24]). As GPS and pedometric estimates of metabolic rates of soldiers in the field improve, it will be possible to quantitatively calculate daily energy, fat, and carbohydrate requirements.

The choice of fuel for exercising muscles is limited to fat and carbohydrate (protein is a minor fuel source)(60). Quantifying the amounts of dietary carbohydrate and fat needed by physically active soldiers requires minute-by-minute information on the intensity, duration, frequency and type of exercise. In future studies, knowing the metabolic cost of locomotion (from GPS and/or pedometry), and the aerobic fitness of each soldier, derived, for example, from Annual Physical Fitness Test 2 mile run times (46), the individual carbohydrate and fat requirements can be calculated. This would help solve the pressing problem of designing field rations that meet the requirements of physically active soldiers (see review by Friedl and Hoyt, 1997 [21]).

Table 6. Previous studies of military personnel where TDEEs were measured by the doubly labeled water method.

TDEE kcal/d (MJ/d)	N	Duration (d)	Subjects and venue	Ref.
3109 ± 543	6	21	U.S. Marines, admin. staff, warm weather, Bahamas	Tharion et al., 2000 (70)
3310 ± 600	11	7	Australian soldiers, naval base duties	Forbes-Ewan et al., 1990 (17)
3330 ± 850	8	28	Special Op. Forces soldiers, field training, high fat rations	DeLany et al., 1989 (11)
3460 ± 732	10	21	US Marines, combat engineers, warm weather, Bahamas	Tharion et al., 2000 (70)
3540 ± 510	8	28	Special Forces soldiers, field training, normal field rations	DeLany et al., 1989 (11)
3550 ± 610	11	10	US Army soldiers, construction, high altitude, Bolivia	Edwards et al., 1991 (13)
3568 ± 741	3	16	US soldiers, transportation co., in garrison, warm weather	Tharion et al., 1998 (71)
3937 ± 550	12	12	Israeli soldiers, hot weather, field training	Burstein et al., 1994 (3)
4070 ± 840	6	63	US Army Ranger students, field training, summer 1991	Hoyt et al., 1993 (31)
4090 ± 470	6	65	US Army Ranger students, field training, summer 1992	Hoyt et al., 1993 (31)
4115 ± 724	19	12	US Marines, artillery unit, desert conditions	Tharion et al., 1997 (69)
4150-5390	4	7	Australian soldiers, jungle warfare training	Forbes-Ewan et al., 1989 (18)
4280 ± 720	18	12	Israeli soldiers, cool weather field training	Burstein et al., 1995, 1996 (2,4)
4320 ± 927	10	10	Canadian soldiers, arctic training	Jones et al., 1993 (38)
4518 ± 625	8	8	US Rangers, garrison training, warm weather	Tharion et al., 1998 (71)
4560 ± 570	6	6	Special Op. Forces, Mt. Rainier ascent	Hoyt et al., 1994 (27)
4920 ± 910	23	11	US Marines, cold weather mountain warfare training	Hoyt et al., 1991 (29)
5185 ± 679	8	8	US Rangers, field training, warm weather	Tharion et al., 1998 (71)
7450 ± 980	12	7	Norwegian ranger cadets, sustained activity, food and sleep deprivation	Hoyt et al., 1996 (32)

Values are mean±SD; kcal · 4.186 = kJ

Were Caloric Intakes During The 10 Day IOC Field Exercise Sufficient To Meet Energy Expenditures?

As expected, TDEEs far exceeded caloric intakes. Marines and soldiers consuming field rations are typically in negative energy balance even though mission requirements, environmental conditions, body size, and load carried vary widely (1,20). With rare exception, the energy needs of soldiers during 5–60 day field training exercises (FTXs) are not met by dietary intake, regardless of ration availability (1,21,26). Field ration consumption is usually less than 3000 kcal/d (12.56 MJ/d), while TDEEs commonly exceed 4000 kcal/d (16.74 MJ/d).

Of the ~5400 kcal/d (22.60 MJ/d) TDEE in the present study, about ~3000-3500 kcal/d (12.6-14.65 MJ/d) was apparently derived from body fat and carbohydrate stores, about 1400 kcal/d (5.86 MJ/d) came from ration consumption, and the balance from unreported food consumption. Factors suggesting that food was consumed but not recorded in the food logs include the smaller than expected 3.3 kg weight loss (~4% of body weight), and the modest estimated loss of body fat. The consumption of unrecorded food probably occurred after the move to a simulated ship board environment at Camp Upshur on days 8–10.

What Are The Consequences Of Undereating?

Fat. Human body energy reserves are almost entirely fat (~98%), with only a modest amount stored as carbohydrate (63). In young males, about 5% of the total body fat percentage serves structural or functional purposes and is not available as a fat energy reserve (23). Thus, body fat energy reserves can be estimated as the product of (a) fractional body fat energy reserves (i.e., body fat minus inaccessible fat, expressed fractionally), (b) body weight, and (c) the conversion factor of 9 kcal/g fat (37.67 kJ/g fat). Protracted, high-intensity field training can deplete fat reserves and result in high rates of loss of lean tissue and borderline starvation (23).

In the present study, fat energy reserves averaged ~76,000 kcal (~318 MJ)(at 81 kg body weight and 15% body fat), but ranged 6-fold, from a modest 24,000 kcal (100 MJ) at ~9% body fat to ~130,000 kcal (544 MJ) at 20% body fat. This wide range of fat reserves is typical of young infantrymen (73). In the present study, the typical Marine used about a quarter of his fat energy reserves, while the leanest Marine may have used up to 2/3 of his fat reserves. The use of body fat energy reserves is inevitably accompanied by some loss of lean tissue. With prolonged underfeeding, lean mass usually accounts for about ¼ of the weight lost, with fat accounting for the remaining 3/4, although the contribution of lean tissue can increase with an extreme energy deficit (16).

Protein. The protein intake of the IOC Marines (43±7 g/d or about 0.6 g/kg BW/d) was about 3/4 the recommended daily allowance of ~60 g/d (0.8 g/kg BW/d) for males fed to energy balance. The importance of this low protein intake is overshadowed by the negative energy balance and, more specifically, the negative carbohydrate balance of these Marines.

Energy balance has a direct influence on apparent protein needs, the amount of dietary protein needed to maintain nitrogen balance decreases as energy intake increases.

Although the effect of dietary fat on protein turnover is unclear, carbohydrate consumption has a powerful influence on protein turnover. Possible mechanisms include (a) carbohydrate-induced increases in insulin lead to increased protein synthesis and decreased protein breakdown, and (b) increased carbohydrate intake decreases hepatic gluconeogenesis, reducing the diversion of amino acids from skeletal muscle. Thus, providing supplemental carbohydrates decreases protein breakdown and helps ensure that protein intakes are adequate even when energy expenditure is high and food intake is restricted. The importance of dietary protein for soldiers and Marines in the field is reviewed elsewhere (35).

Carbohydrate. The 140 g/d dietary CHO intake of the IOC Marines was far less than the 400 g/d or more needed for adequate liver and muscle glycogen repletion (1,34,36,63). When body glycogen stores are reduced by exercise and/or a low CHO diet, there is a switch to a fat-predominant fuel metabolism (7,28,58), with as much as a 50% reduction in endurance exercise capacity (8,14), and a loss of lean body mass (16,43).

Providing Marines and soldiers with carbohydrate beverage is an effective way to increase carbohydrate and total caloric intakes, and to improve endurance exercise capacities (34,38,51,47,48). Solid high carbohydrate food stuffs seem to be less effective (12,13) than maltodextrin-based carbohydrate beverages at increasing voluntary carbohydrate consumption (38,48). In a desert environment, soldiers provided with a maltodextrin-based carbohydrate beverage had substantially higher carbohydrate intakes (310 g/d vs. 460 g/d) and higher total caloric intakes (2500 kcal/d vs. 3000 kcal/d)(10.5 MJ/d vs 12.6 MJ/d) than a placebo control group (69). A controlled metabolic ward study of physical performance in Special Operations soldiers consuming a military diet showed that consumption of a maltodextrin carbohydrate beverage during sustained physical activity improved endurance exercise performance by 16% (51).

THERMAL STATUS

Is There Any Evidence Of Hypothermia, And When Is The Risk Of Hypothermia Greatest?

Overt hypothermia, that is, core temperatures (Tc) below 35.5 °C, was not evident during the FEX. However, with the apparent onset of sleep, Tc decreased rapidly in association with increased wrist skin temperature (e.g., 5 March/ Day 3 and 8 March/Day 6, Figure 5). This pattern of vasodilation, increased skin temperature, and decreased Tc with sleep is well known (25,41,42). However, the mean rate of decline in Tc with sleep was unusually rapid in the Marines ($\sim -1^{o}C \bullet h^{-1}$). For example, Figure 6 shows the cold stress associated with a transition from a 6 km movement in full gear to inactivity. Such high rates of cooling, which were two to three fold the normal rate of cooling, are typically associated with an increase in the number and duration of arousals and other evidence of disrupted sleep (52). One way to limit the rate of cooling and improve the quality of sleep during cold weather FEXs may be to provide Marines with the new 3-piece Modular Sleeping Bag System (MSBS). The lightweight bivy sack portion of the MSBS alone might reduce the likelihood of the “travel light, freeze at night” syndrome seen in this study.

In its unmodified form, the CSI equation (50) was unresponsive to falling core temperature due to the counterbalancing effect of the rising skin temperatures. When modified to eliminate the effects of rising skin temperature, the CSI gave some indication of the cold stress experienced by the Marines. In contrast, the PSI equation (49) appeared to be a more sensitive indicator of the heat strain experienced by the IOC Marines. Although conditions were cold/wet or cold/dry, moderate increases in heat strain were occasionally evident, for example, during a fast-paced mid-day march (Figure 7).

Figure 6. Calculated Cold Strain Index (CSI) values (n= 7) for 8 March 1999/Day 6.

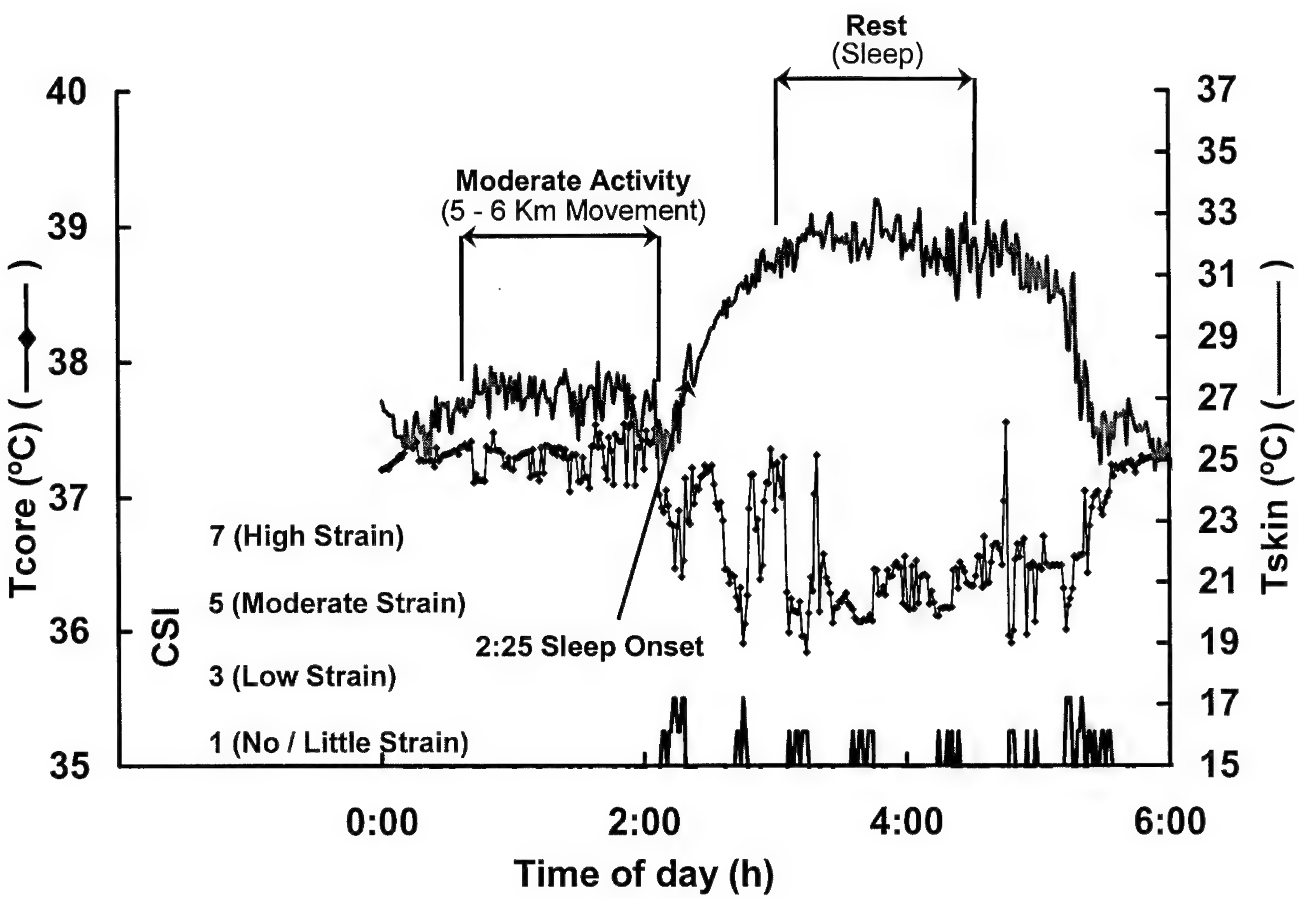
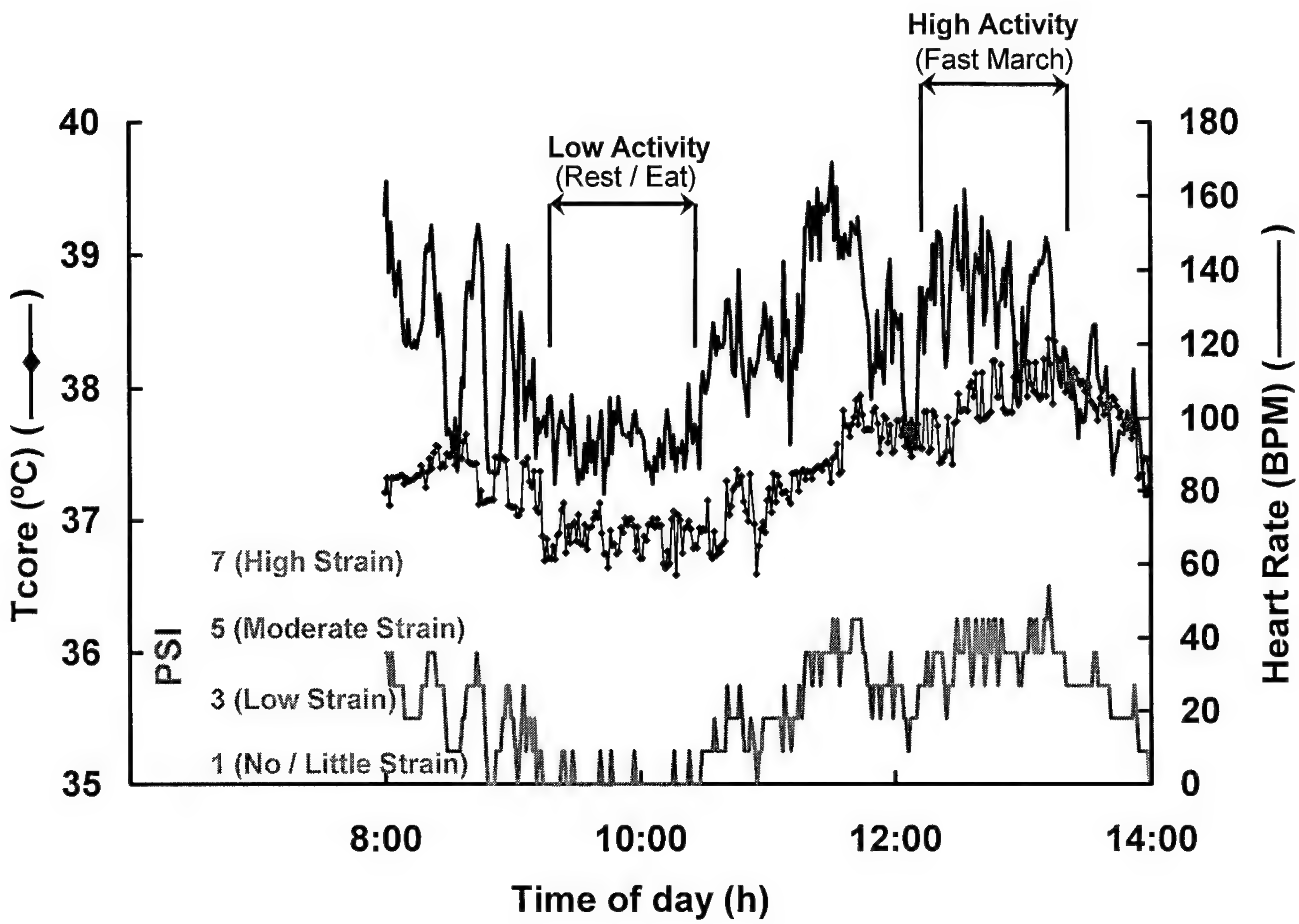


Figure 7. Calculated Physiological Strain Index (PSI) values (n= 7) for 7 March 1999/Day 5 reflect work/heat strain.



RECOMMENDATIONS

- Provide Marines with 200 to 300 g/d of a supplemental carbohydrate beverage powder to correct dietary carbohydrate shortfall during FEXs.
- Consider instituting systematic refeeding during the last 3 days of the FEX.
- Use bivy sack to avoid rapid cooling and sleep disruption in cold/wet conditions.

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APPENDIX A

Wind speeds during IOC field exercise

Wind speed ($m \cdot s^{-1}$) during the 10 day field exercise (3 to 12 March 1999) expressed as mean and (SD) by six hour period.

Time:	0000-0600	0600-1200	1200-1800	1800-2400
Day				
1	3.33 (1.32)	3.60 (1.45)	4.22 (1.31)	1.37 (0.72)
2	0.67(0.33)	0.97 (0.52)	1.99 (0.68)	2.99 (0.44)
3	2.99 (0.63)	2.55 (0.68)	2.87 (0.74)	2.48 (1.41)
4	4.68 (0.99)	4.74 (1.05)	3.81 (0.91)	2.29 (0.55)
5	2.44 (0.43)	2.81 (0.75)	2.57 (0.71)	0.56 (0.31)
6	0.57 (0.58)	1.23 (0.63)	1.57 (0.38)	0.84 (0.48)
7	0.87 (0.28)	1.35 (0.49)	2.27 (0.64)	1.45 (0.64)
8	2.84 (0.62)	3.17 (1.22)	3.45 (0.92)	3.01 (0.89)
9	3.67 (1.07)	3.91 (1.26)	4.63 (0.97)	3.19 (0.76)
10	3.12 (0.89)	2.89 (0.83)	---	---
Mean	2.52	2.72	3.04	2.02
SD	1.39	1.23	1.05	0.99

APPENDIX B. Field exercise clothing log.

	Kevlar helmet	scarf	Ski-Mask	undershirt	Poly-pro Undershirt	poly--pro turtleneck	Cotton Long-John Top	BDU-Jacket Cold Weathe	Flak Jacket	Gore-Tex Jacket	Wet Weather Top	Gloves Gore-Tex	Gloves Issue Leather	Gloves Issue Wool Liner	Poly-pro Bottom	BDU Pants Cold Weather	Socks Wool	Socks Cotton	Matterhorn Boots	Danner Boots	Issue Combat Boots	Sleeping Bag	Sleeping Bag Cover	*Additional Clothing Worn*
SN1 Day																								
Night																								
Sleep																								
SN2 Day	X	X	X	X	X	X		X	X		X			X	X	X	X	X	X					**Field Jacket Liner**
Night	X	X	X	X	X	X		X	X		X			X	X	X	X	X	X					**Field Jacket Liner**
Sleep		X	X	X	X	X		X			X			X	X	X	X	X				X	X	**Field Jacket Liner**
SN3 Day	X		X	X	X			X	X		X			X	X	X	X			X		X	X	**North Face Vest**
Night	X		X	X	X			X	X		X			X	X	X	X			X		X	X	
Sleep			X	X	X			X							X	X				X		X	X	
SN4 Day	X	X		X	X			X	X		X			X	X	X	X			X				
Night		X		X	X			X	X		X			X	X	X	X			X				
Sleep		X		X	X			X						X	X	X	X							
SN5 Day	X	X			X			X	X						50%	X	X		X					
Night		X			X	X		X							X	X	X		X					
Sleep								X							X	X	X		50%			X	X	
SN6 Day	X	X		X				X	X			X					X				X			
Night	X	X		X	X			X	X			X			X		X				X			
Sleep								X	X			X			X		X				X	X	X	
SN7 Day	X				X			X	X						X	X		X	X					**Seal Skin Gloves, Silk Long-Johns**
Night	X	X			X	X		X	X		X				X	X		X	X					
Sleep					X			X	X						X	X		X	50%					
SN8 Day	X			X	X			X	X		X		X			X				X				
Night	X			X	X			X	X		X		X		X	X				X				**Black Wool Cap, Field Jacket Liner, Thorlo-**
Sleep					X			X			X				X	X				X		X	X	**Combat Boot Socks, Poly-pro Sock Liners**
SN9 Day	X			X		X		HW	X		X		X	X		HW	X			X				
Night	X	X		X		X		HW	X		X		X	X	X	HW	X			X				
Sleep				X		X		HW							X	HW	X			X		X	X	
SN10 Day	X	X		X	X	X	X	X	X		X	X		X	X	X	X	X	X			X	X	**Dive Jocks Beanie**
Night	X	X		X	X	X	X	X	X		X	X		X	X	X	X	X	X					
Sleep		X		X	X	X	X	X	X		X				X	X	X	X	X					
SN11 Day	X	X	X	X		X		X	X		X			X		X	X			X				
Night	X	X	X	X		X		X	X							X	X			X				
Sleep		X	X	X		X		X								X	X					X	X	
SN12 Day	X	X		X	X			X	X					X	X	X		X	X					**Field Jacket Liner, Black Watch Cap**
Night	X	X		X	X			X	X					X	X	X		X	X					
Sleep					X										X	X		X	X			X	X	
SN13 Day	X	X		X	X		X	X	X		X	X	X		X	X	X			X				
Night	X	X		X	X		X	X	X		X	X	X		X	X	X			X				
Sleep		X		X	X		X	X	50%		X					X	X			X		50%		
SN14 Day		X		X	X			X	X					X	X		X		X					
Night		X		X	X			X	X					X	Xl		X		X					
Sleep																	X					X		